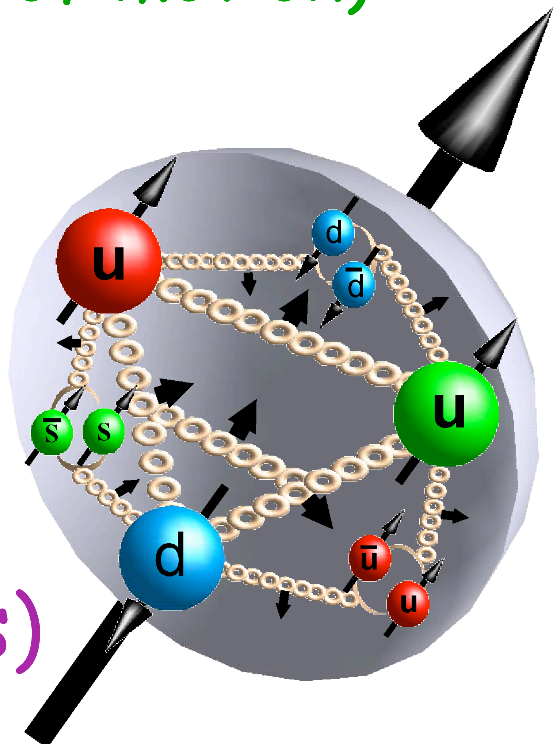
Central object of investigation: the proton transverse internal structure, that is the quark transverse spin and transverse motion (with respect to the direction of motion)

Why transverse? How?

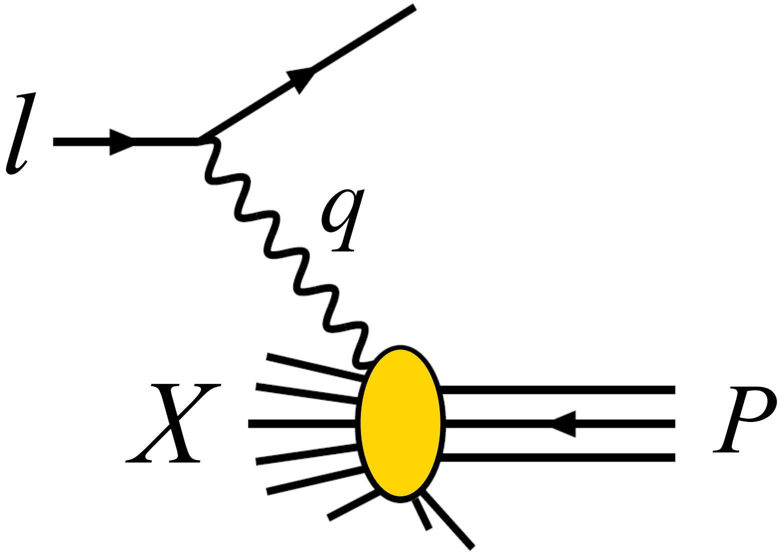
Single Spin Asymmetries

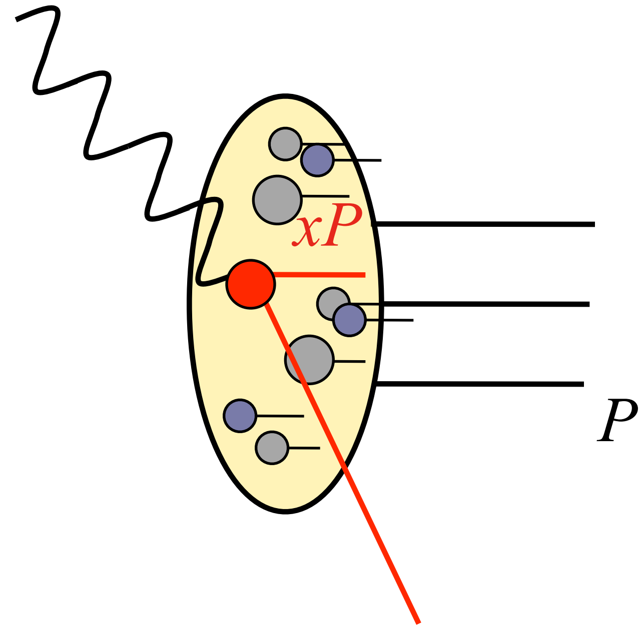
Transverse Momentum Dependent distribution and fragmentation functions (TMDs)



Combining all together and learning...

How and what do we know about the longitudinal proton structure?

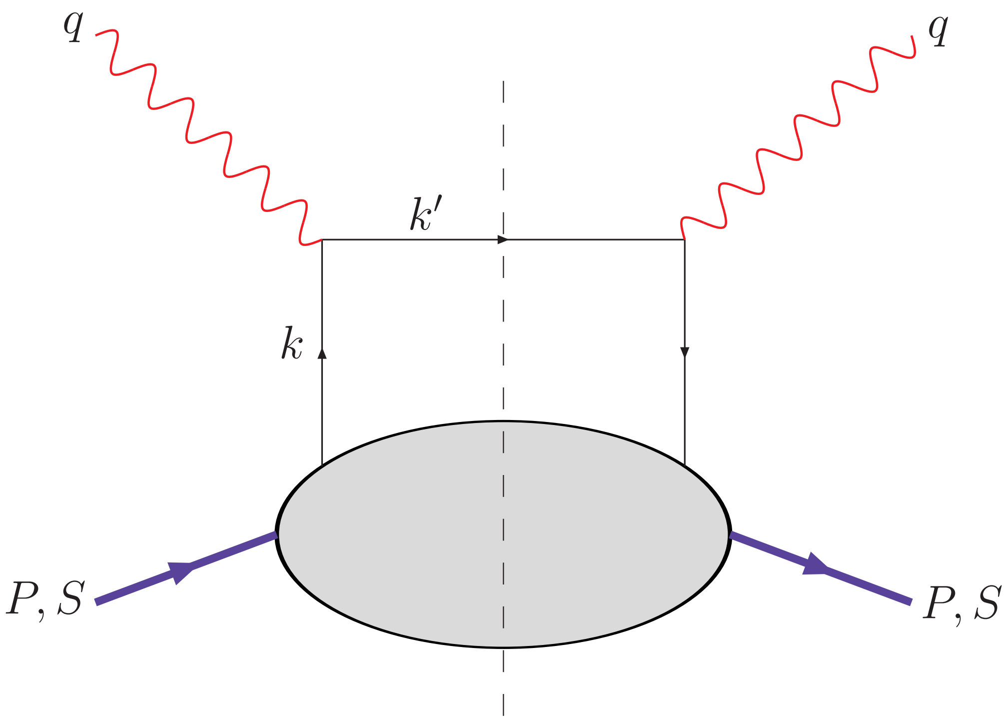




$$\mathrm{DIS}:\ \ell\, p \to \ell\, X \qquad Q^2 = -q^2 \qquad x = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot \ell}{P\cdot q}$$

Naive parton model:
$$\frac{\mathrm{d}\sigma^{\ell p\to \ell X}}{\mathrm{d}x\,\mathrm{d}Q^2} = \sum_q e_q^2\, q(x)\, \frac{\mathrm{d}\hat{\sigma}^{\ell q\to \ell q}}{\mathrm{d}Q^2}$$

Total cross section for $\gamma^* p \to X$ process
= imaginary part of forward scattering amplitude

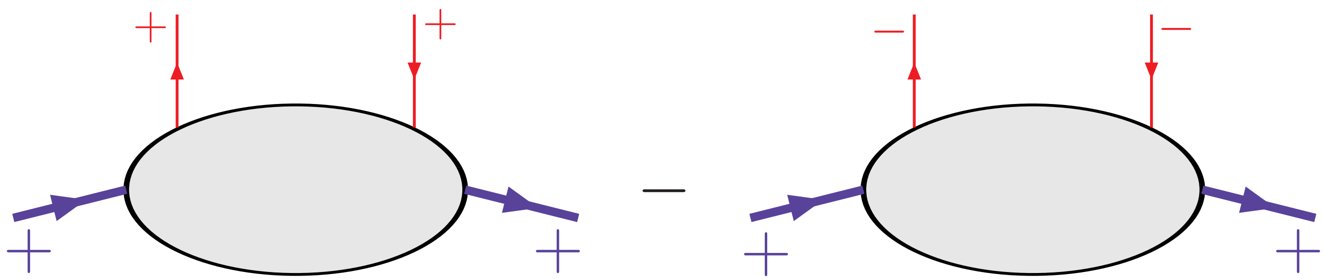


handbag diagram

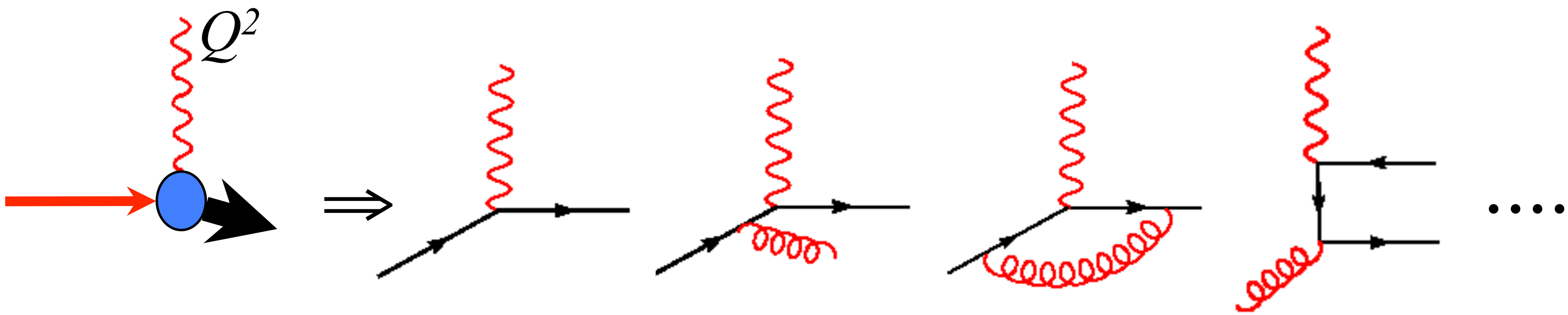
Longitudinally polarized DIS gives information on the helicity distributions of quarks (and, indirectly, of gluons)

$$\frac{d\sigma^{\overbrace{+,+}^{\lambda_l\,\lambda_p}}}{dx\,dy} - \frac{d\sigma^{+,-}}{dx\,dy} = \sum_q e_q^2\,\Delta q(x)\left[\frac{d\hat\sigma^{\overbrace{+,+}^{\lambda_l\,\lambda_q}}}{dy} - \frac{d\hat\sigma^{+,-}}{dy}\right]$$

$$\Delta q(x) = q_+^+(x) - q_-^+(x)$$



QCD interactions induce a well known Q^2 dependence

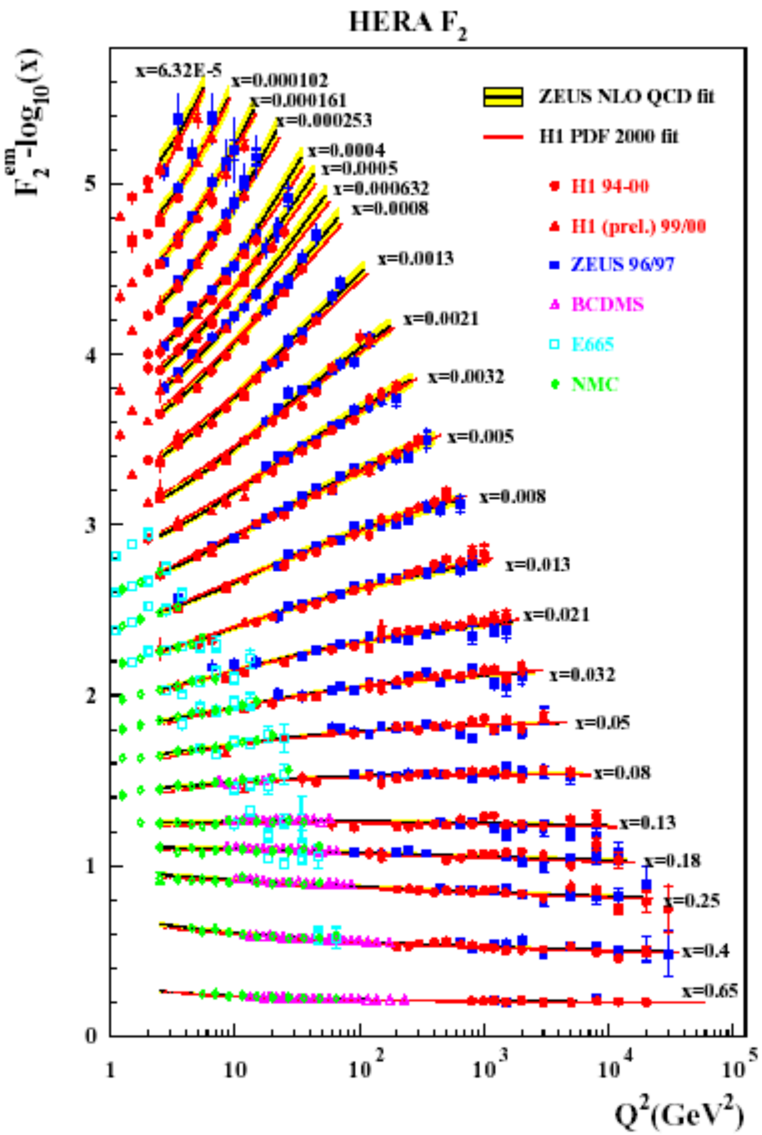


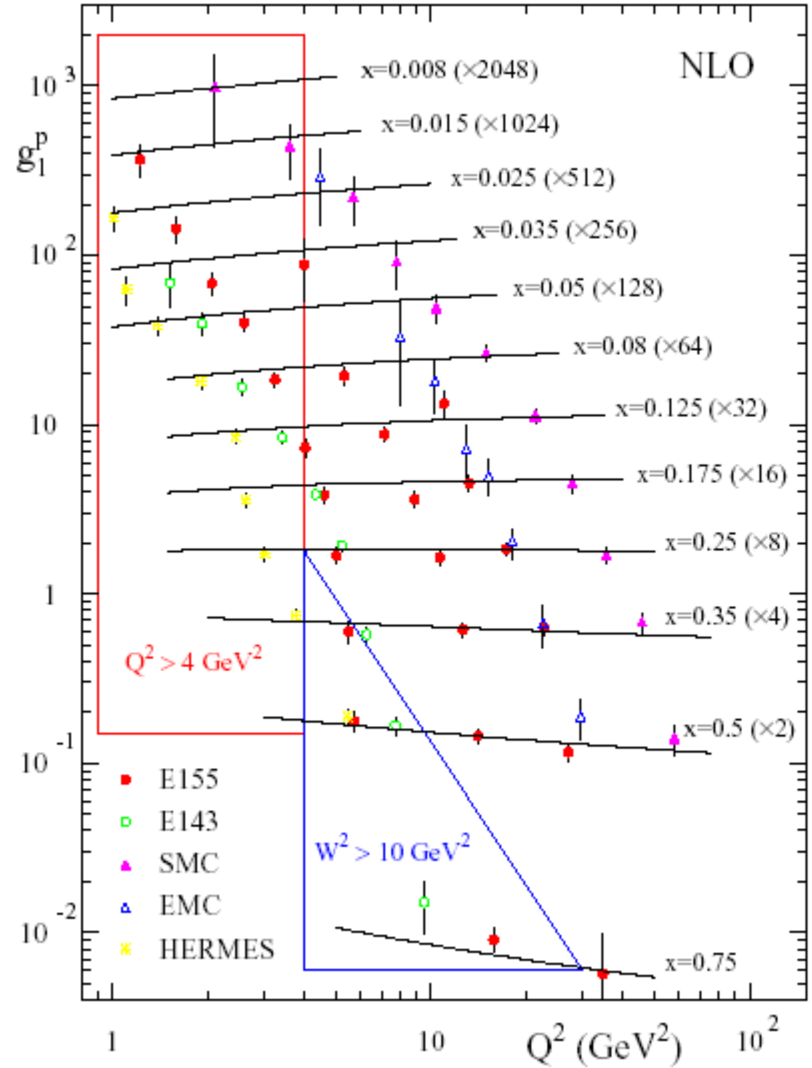
$$\mathrm{DIS-pQCD:}\quad q(x) \Rightarrow q(x,Q^2)$$

factorization:

$$\frac{d\sigma^{\ell p\to\ell X}}{dx\,dQ^2} = \sum_q e_q^2\, q(x,Q^2)\,\frac{d\hat{\sigma}^{\ell q\to\ell q}}{dQ^2}$$

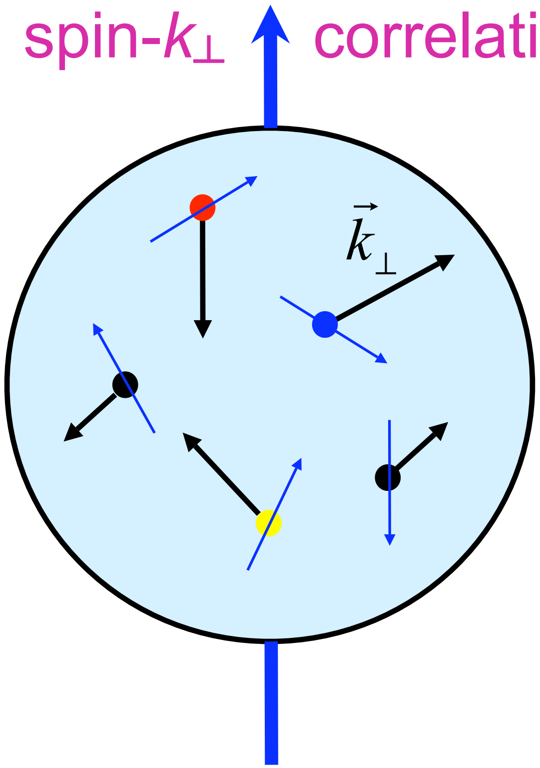
universality: same $q(x,Q^2)$ measured in DIS can be used in other processes essentially *x* and Q^2 degrees of freedom ….





The transverse structure is much more interesting and less studied

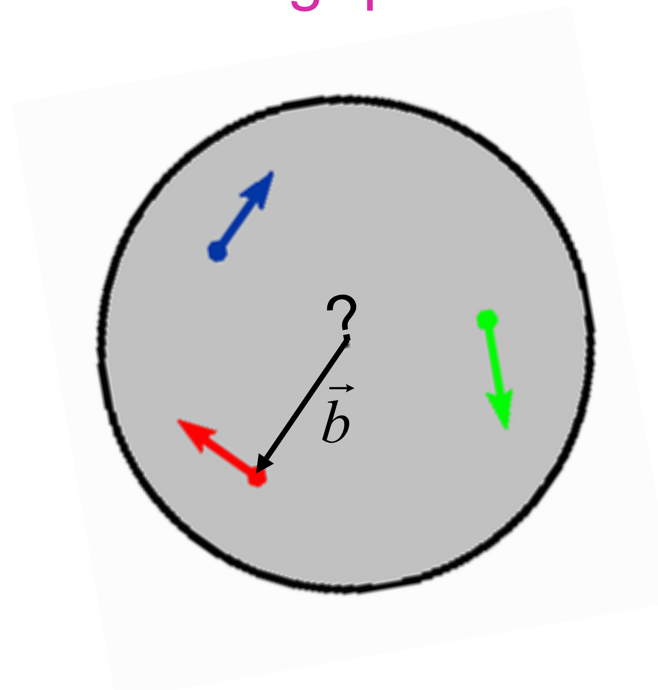
spin-$k_\perp$ correlations?



Transverse Momentum Dependent distribution functions

$$q(x, \boldsymbol{k}_\perp; Q^2)$$

orbiting quarks?

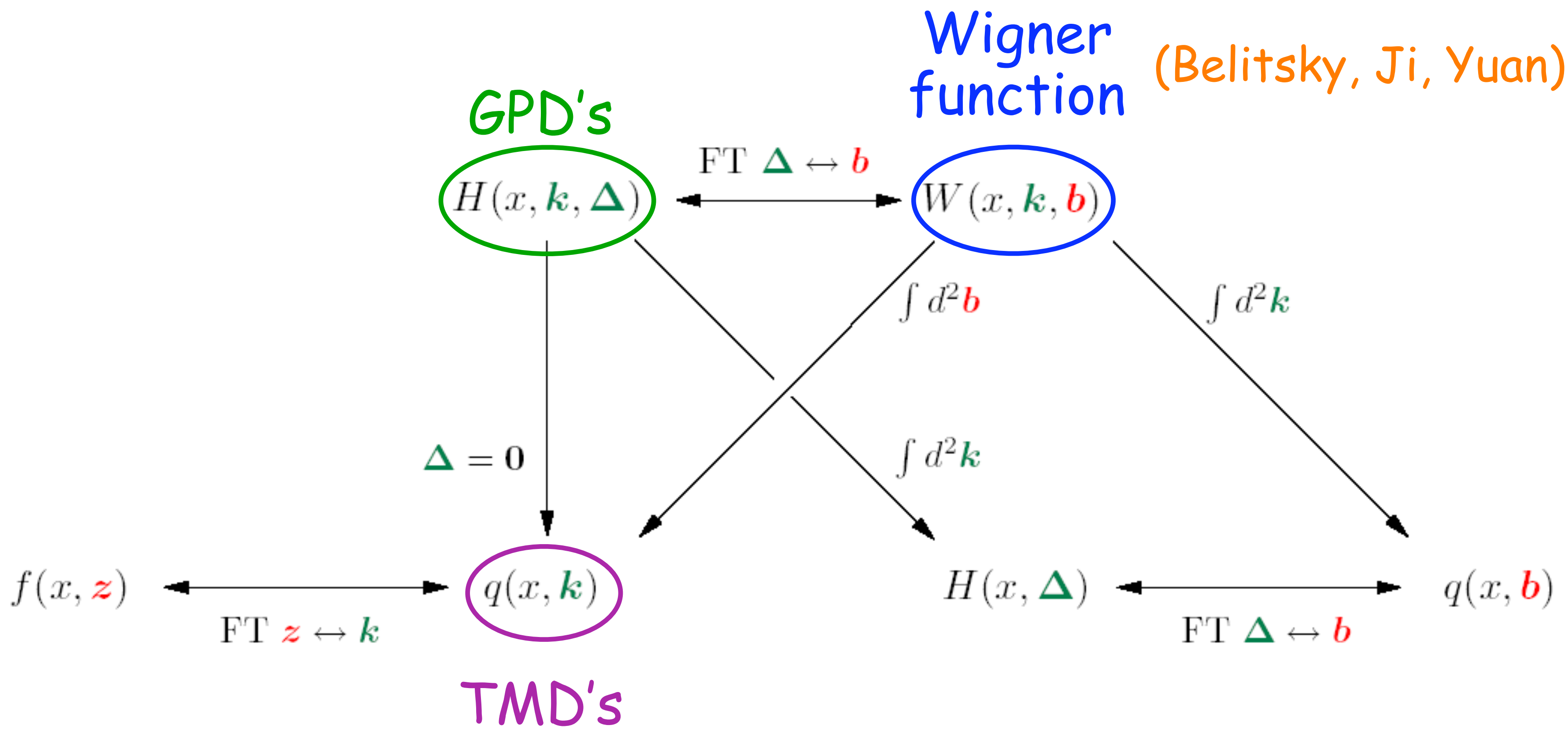


Space dependent distribution functions

$$q(x, \boldsymbol{b}; Q^2)$$

The mother of all functions

M. Diehl, Trento workshop, June 07



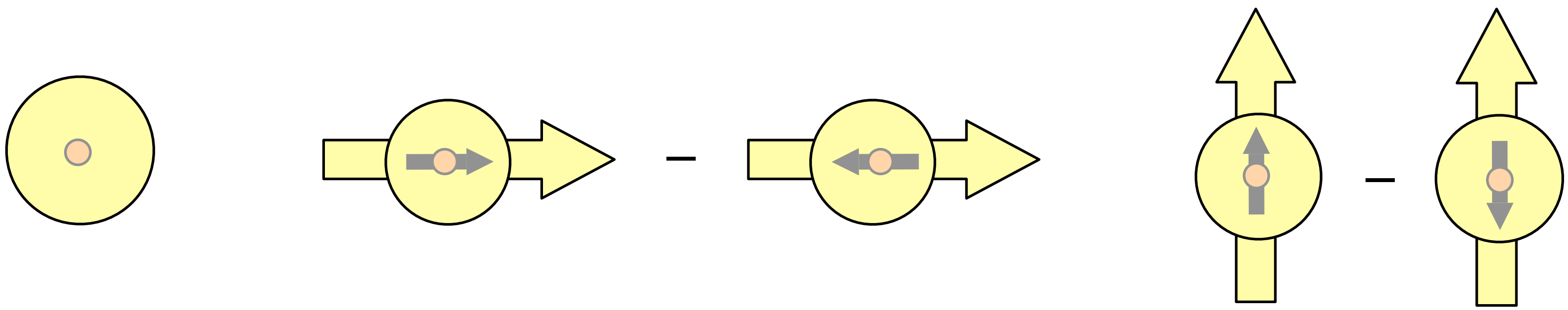
Transversity distribution

$$\boxed{\Delta_T q(x) = q_{\uparrow}^{\uparrow}(x) - q_{\downarrow}^{\uparrow}(x)}$$

$\Delta_T q$ also denoted as h_{1q} or δq

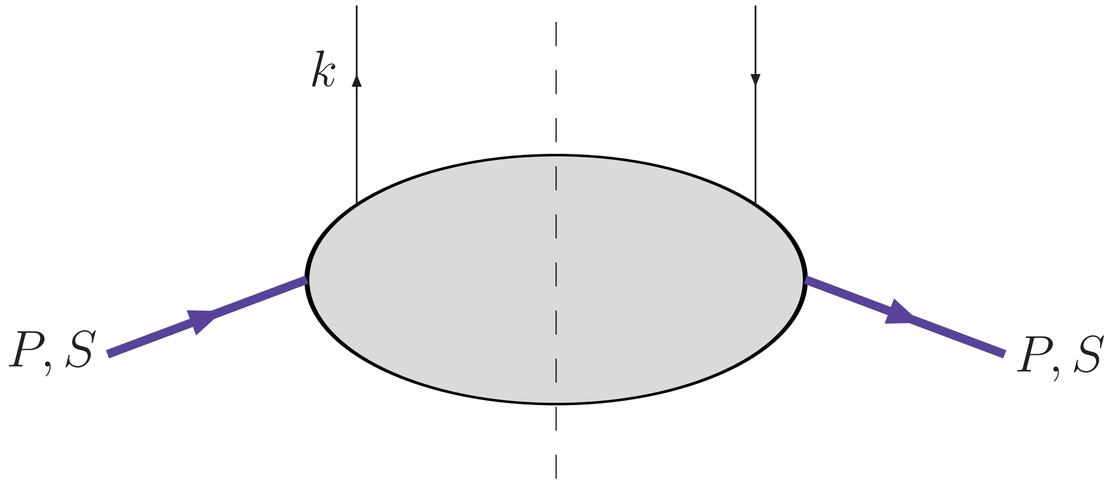
$q(x,Q^2)$, $\Delta q(x,Q^2)$ and $\Delta_T q(x,Q^2)$

are all fundamental, and different, leading-twist quark distributions, equally important



$\Delta_T q = \Delta q$ only for a proton at rest

The correlator



$$\Phi_{ij}(k;P,S) = \sum_X \int \frac{\mathrm{d}^3 \boldsymbol{P}_X}{(2\pi)^3\, 2E_X}\,(2\pi)^4\,\delta^4(P-k-P_X)\langle PS|\overline{\Psi}_j(0)|X\rangle\langle X|\Psi_i(0)|PS\rangle$$

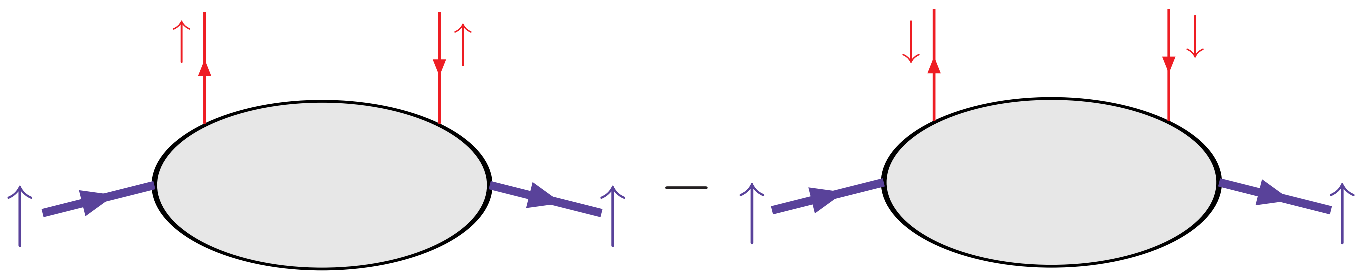
$$= \int \mathrm{d}^4\,\xi\, e^{ik\cdot\xi}\langle PS|\overline{\Psi}_j(0)\Psi_(\xi)|PS\rangle$$

at leading twist, in collinear configuration:

$$\Phi(x,S) = \frac{1}{2}\left[\underbrace{f_1(x)}_{q}\not{n}_+ + S_L \underbrace{g_{1L}(x)}_{\Delta q}\gamma^5\not{n}_+ + \underbrace{h_{1T}}_{\Delta_T q} i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu\right]$$

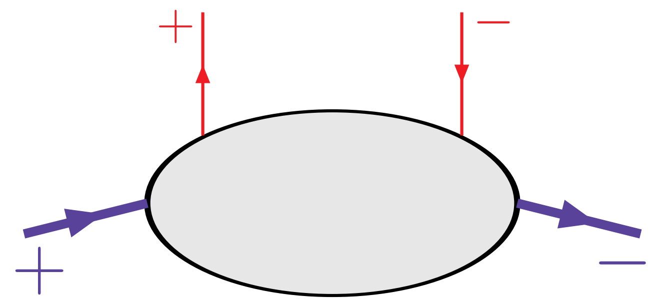
Does transversally polarized DIS give information on the transversity distributions of quarks? No!

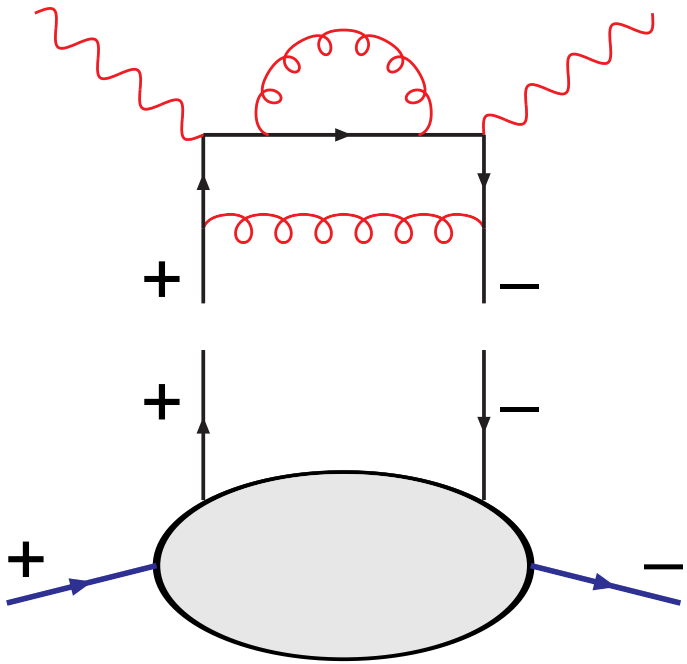
$$\frac{\mathrm{d}\sigma^{\uparrow,\uparrow}}{\mathrm{d}x\,\mathrm{d}y} - \frac{\mathrm{d}\sigma^{\uparrow,\downarrow}}{\mathrm{d}x\,\mathrm{d}y} = \sum_q e_q^2\, \Delta_T q(x)\, \underbrace{\left[\frac{\mathrm{d}\hat{\sigma}^{\uparrow,\uparrow}}{\mathrm{d}y} - \frac{\mathrm{d}\hat{\sigma}^{\uparrow,\downarrow}}{\mathrm{d}y}\right]}_{O(m_q/E_q)}$$



in helicity basis:

$$|\uparrow,\downarrow\rangle = \frac{1}{\sqrt{2}}(|+\rangle \pm i|-\rangle)$$





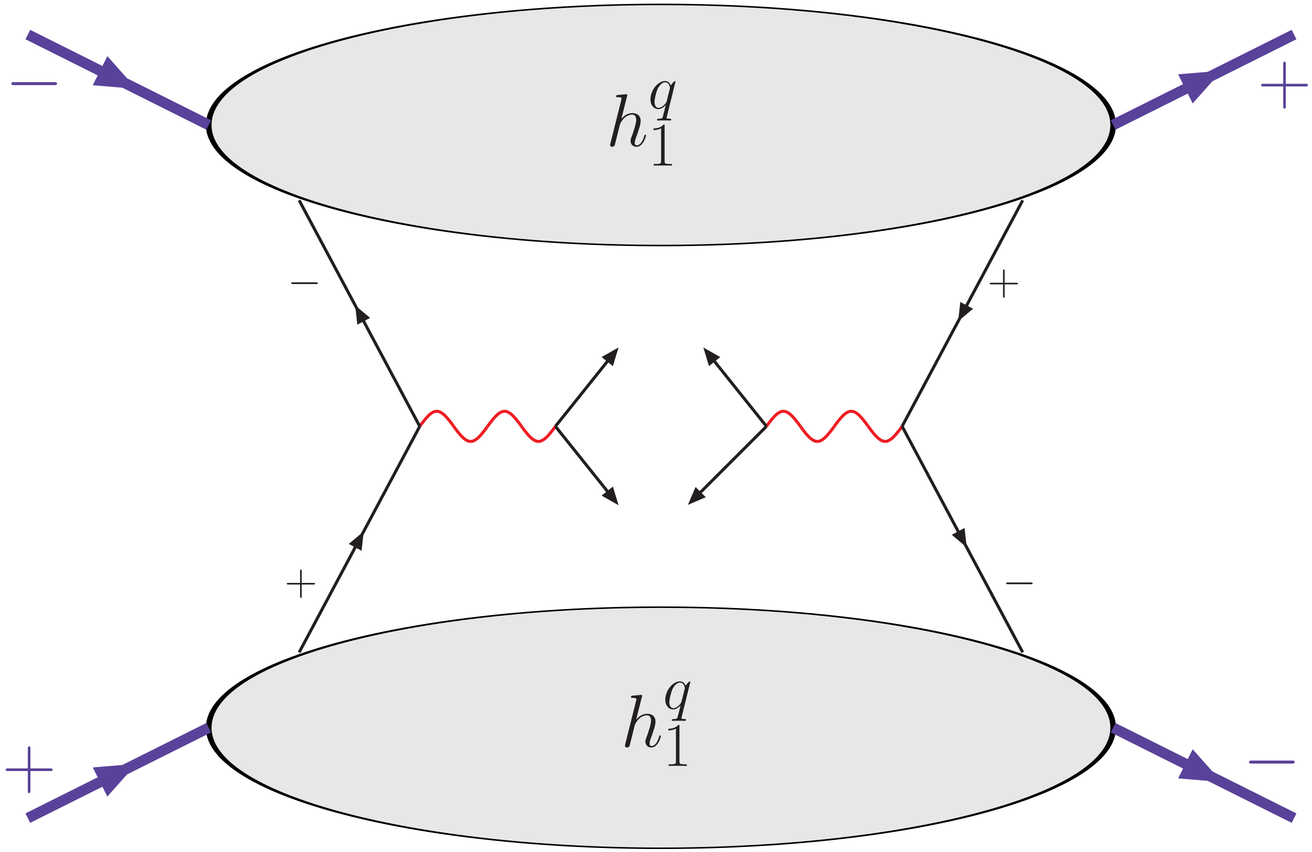
no h_1 in DIS

QED and QCD interations
(and SM weak interactions)
conserve helicity:
h_1 decouples from DIS

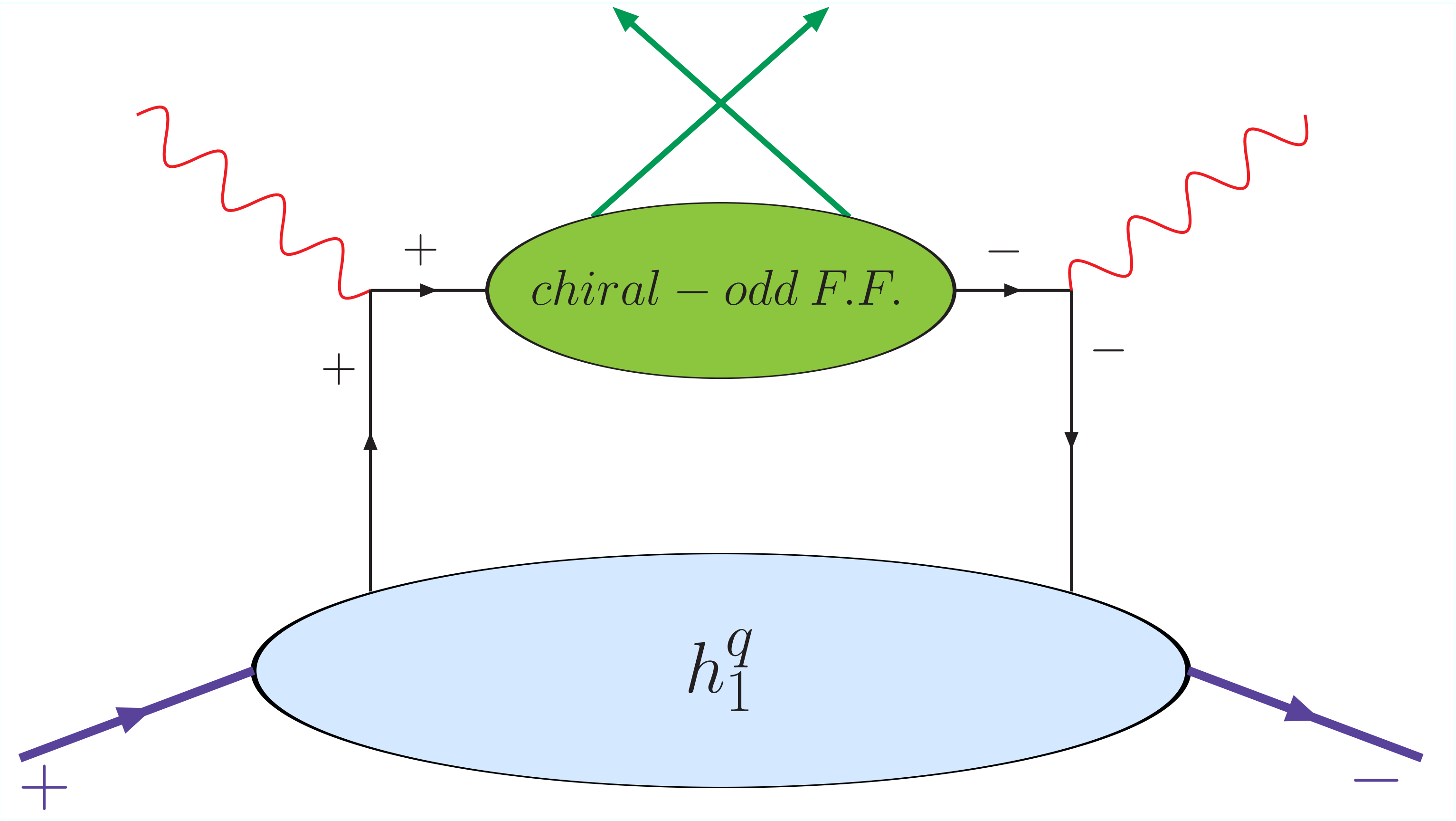
$$\bar{u}_{\lambda_q}(q)\underbrace{\gamma\cdots\gamma}_{\text{odd numbers of gamma matrices}}u_{\lambda'_q}(q') \propto \delta_{\lambda_q,\lambda'_q} + \mathcal{O}\left(\frac{m_q}{E_q}\right)\delta_{\lambda_q,-\lambda'_q}$$

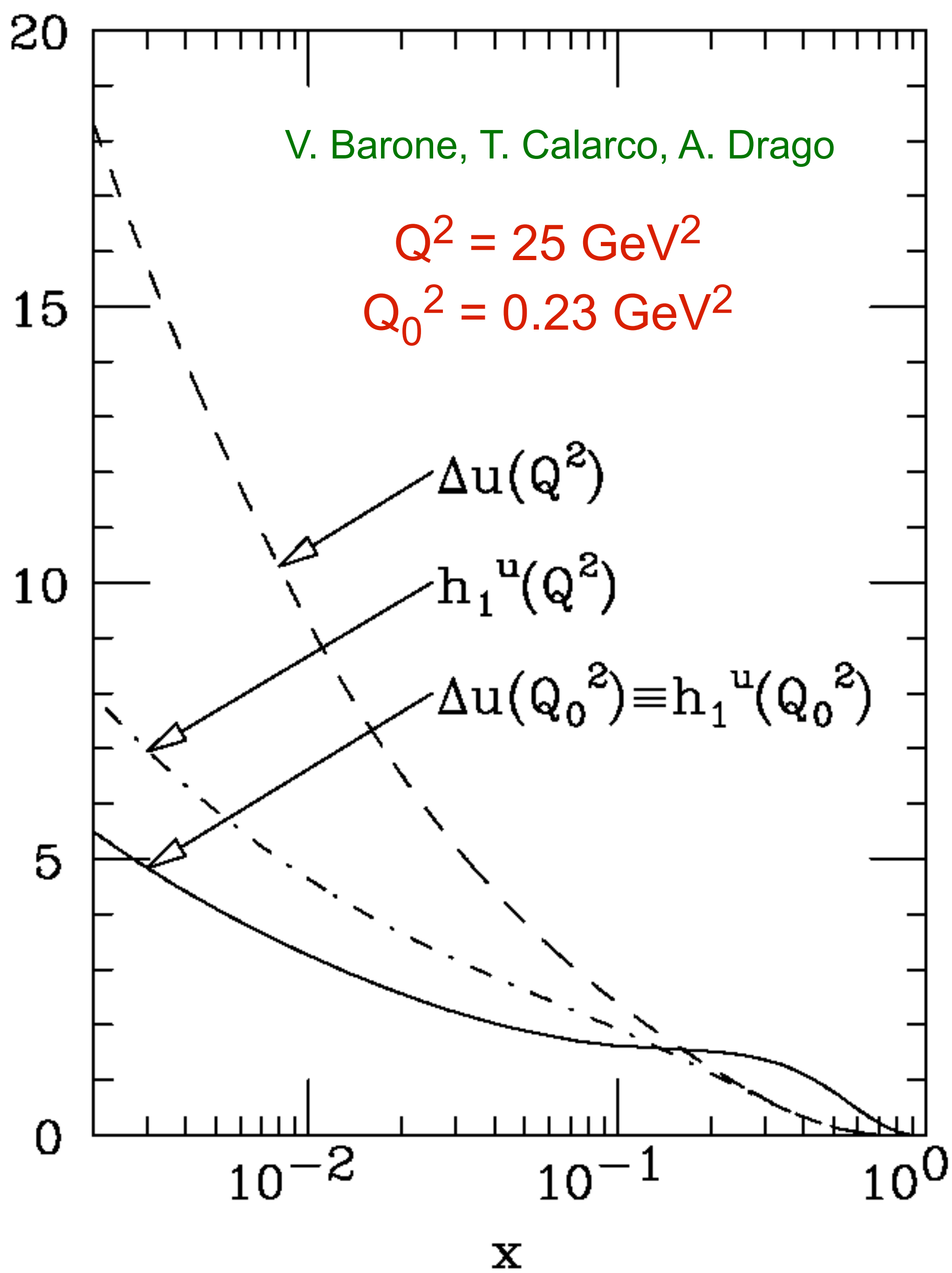
Possible access to transversity: Drell-Yan processes

$$p\,p \to \ell^+\ell^-,\ \pi\,p \to \ell^+\ell^-,\ p\,\bar{p} \to \ell^+\ell^-$$



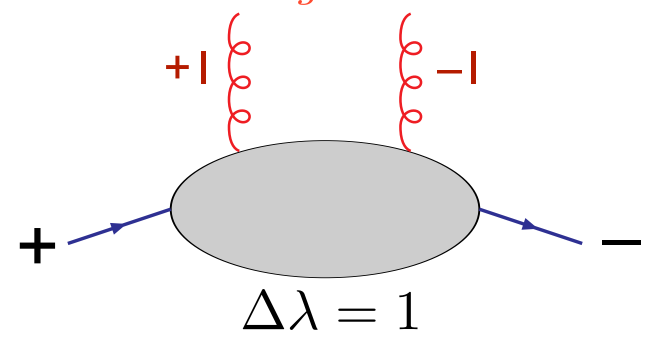
SIDIS, $\ell\, p \to \ell\, h\, X$





What do we know about transversity?

No gluon contribution to h_1, simple Q^2 evolution



Soffer bound

$$\boxed{2\,|\,\Delta_T q\,| \le q + \Delta q}$$

tensor charge from lattice

$$\int_0^1 dx\ \left[h_{1q}(x,Q^2) - h_{1\bar{q}}(x,Q^2)\right]$$

(The problem of) Single Spin Asymmetries

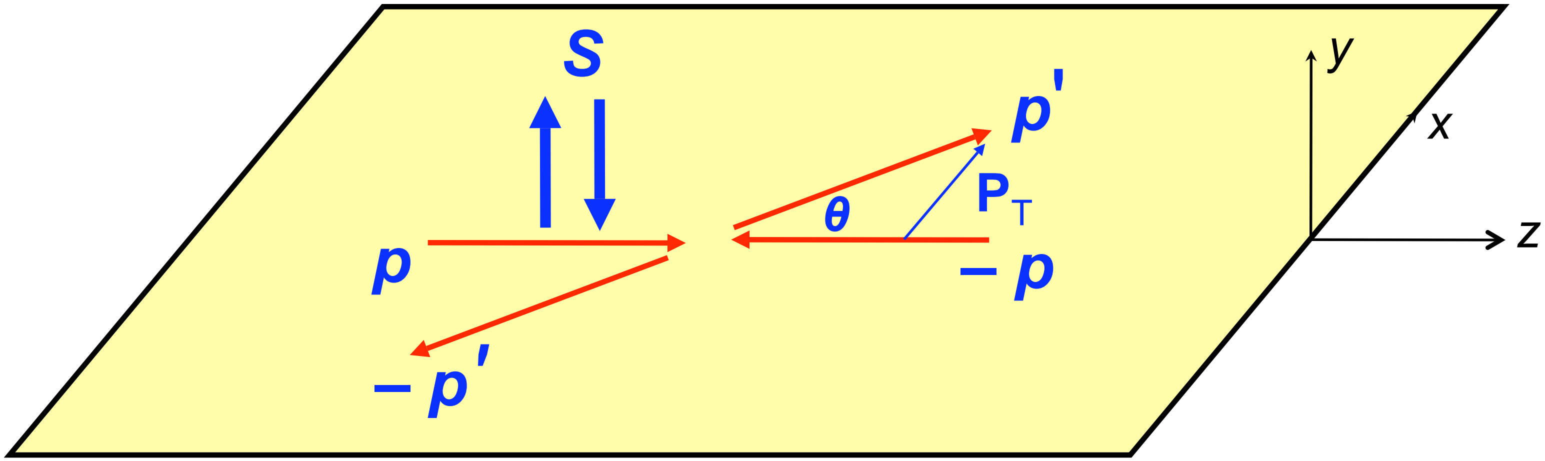
What are SSA?

SSA in QED and QCD, helicity conservation

SSA at hadronic level, experiments

Transverse SSA related to intrinsic partonic motion, new spin effects in distribution and fragmentation functions ….

Transverse single spin asymmetries in elastic scattering



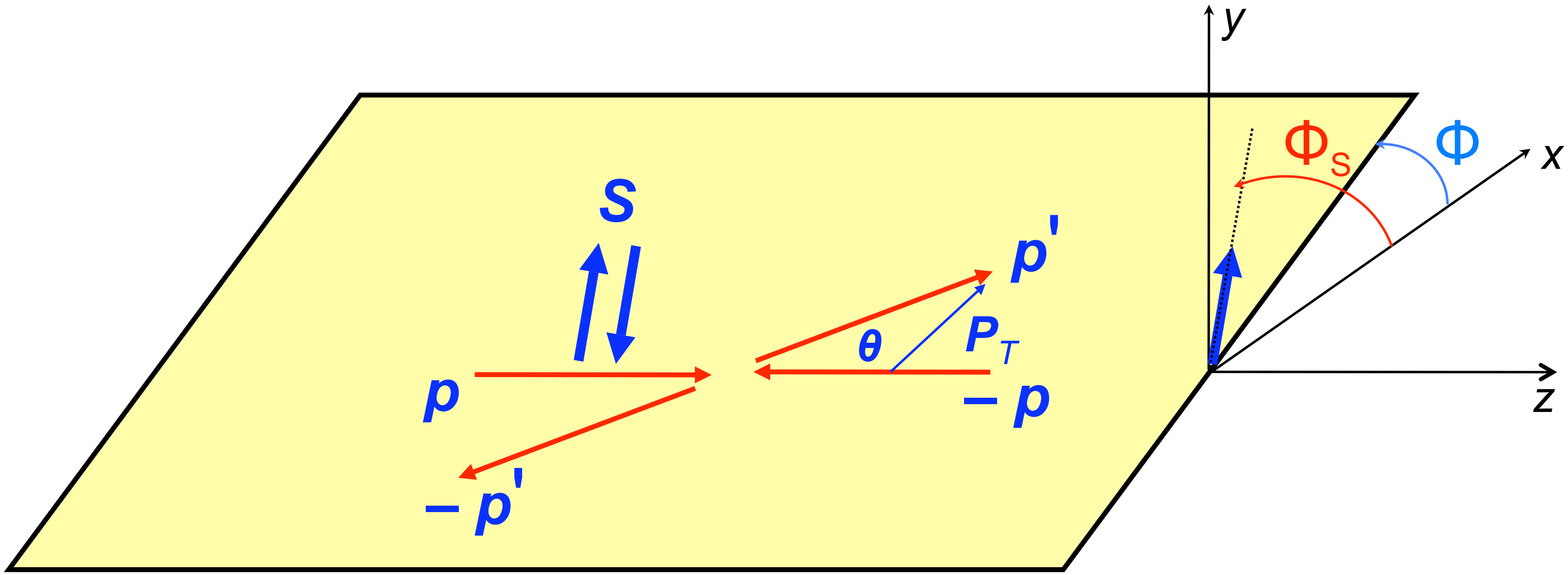
$$A_N \equiv \frac{\mathrm{d}\sigma^{\uparrow} - \mathrm{d}\sigma^{\downarrow}}{\mathrm{d}\sigma^{\uparrow} + \mathrm{d}\sigma^{\downarrow}} \propto \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{P}_T) \propto \sin\theta$$

Example: $p\,p \longrightarrow p\,p$

$$\left\{ \begin{aligned} H_{++;++} &\equiv \Phi_1 \\ H_{--;++} &\equiv \Phi_2 \\ H_{+-;+-} &\equiv \Phi_3 \\ H_{-+;+-} &\equiv \Phi_4 \\ H_{-+;++} &\equiv \Phi_5 \end{aligned} \right.$$

5 independent helicity amplitudes

$$A_N \propto \mathrm{Im}\left[\Phi_5\left(\Phi_1 + \Phi_2 + \Phi_3 - \Phi_4\right)^*\right]$$



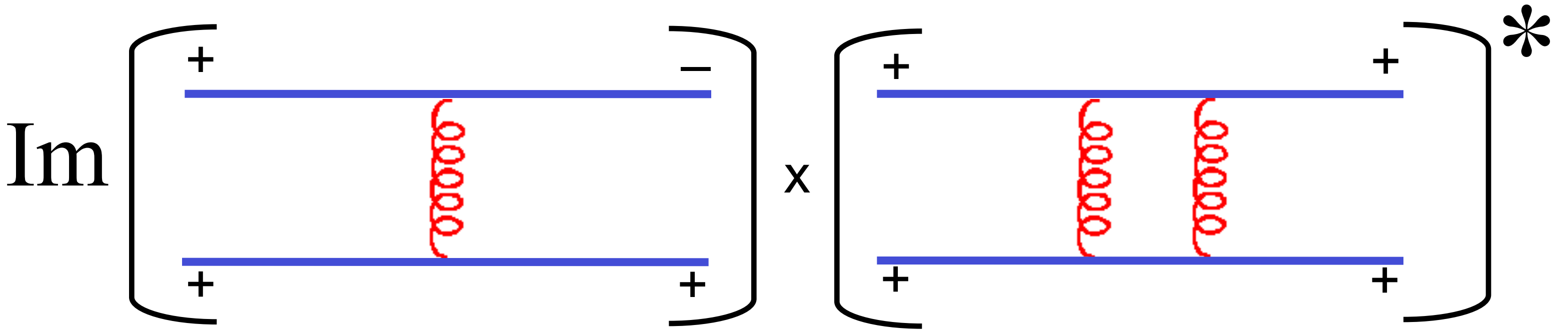
for a generic configuration:

$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{P}_T) \propto P_T \sin(\Phi_S - \Phi)$$

A_N is zero for longitudinal spin

Single spin asymmetries at partonic level. Example: $q\,q' \to q\,q'$

$A_N \neq 0$ needs helicity flip + relative phase



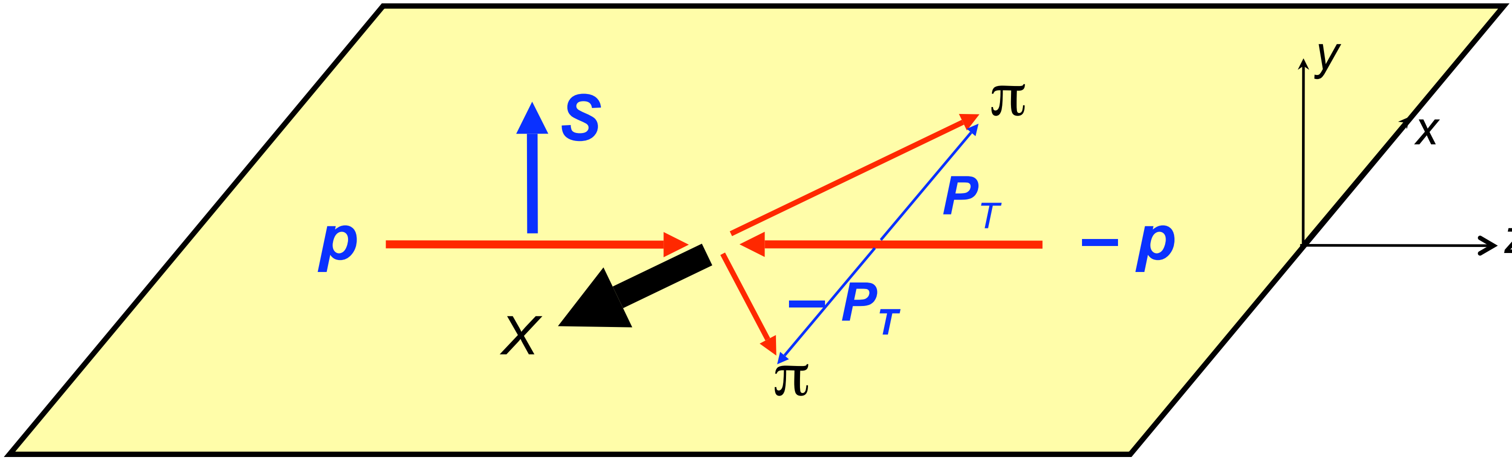
QED and QCD interactions conserve helicity, up to corrections $\mathcal{O}\left(\frac{m_q}{E_q}\right)$

$$\Longrightarrow \quad A_N \propto \frac{m_q}{E_q}\,\alpha_s \quad \text{at quark level}$$

but large SSA observed at hadron level!

SSA in inclusive processes: $p^{\uparrow} p \to \pi X$

$$\boxed{A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}}$$



$$d\sigma^{\downarrow}(\boldsymbol{P}_T) = d\sigma^{\uparrow}(-\boldsymbol{P}_T)$$

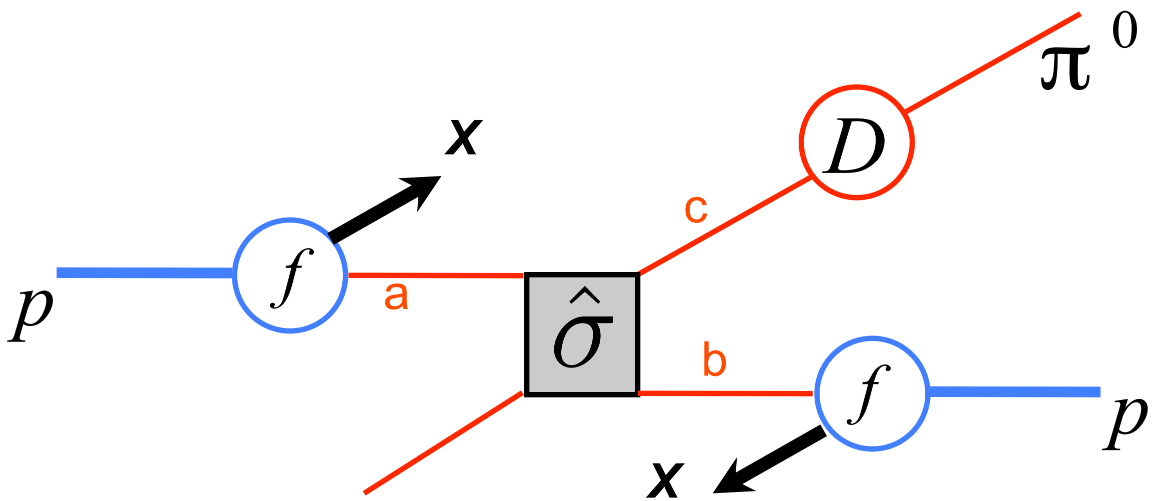
$$d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\downarrow}(\boldsymbol{P}_T) = d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\uparrow}(-\boldsymbol{P}_T)$$

A_N = simple left-right asymmetry

Cross section for $p\,p \to \pi^0\,X$ in pQCD

based on factorization theorem

(in collinear configuration)



$$\mathrm{d}\sigma = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{f_{a/p}(x_a) \otimes f_{b/p}(x_b)}_{\text{PDF}} \otimes \mathrm{d}\hat{\sigma}^{ab\to cd} \otimes \underbrace{D_{\pi/c}(z)}_{\text{FF}}$$

$\mathrm{d}\hat{\sigma}^{ab\to cd}$ → pQCD elementary interactions

exact formula (LO)

$$\frac{E_C\, d\sigma^{AB\to CX}}{d^3\boldsymbol{p}_C} = \sum_{a,b,c,d} \int dx_a\, dx_b\, dz\, f_{a/A}(x_a, Q^2)\, f_{b/B}(x_b, Q^2)$$
$$\times \quad \frac{\hat{s}}{\pi z^2} \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(\hat{s}, \hat{t}, \hat{u}, x_a, x_b)\, \delta(\hat{s}+\hat{t}+\hat{u})\, D_{C/c}(z, Q^2)$$
$$= \sum_{a,b,c,d} \int dx_a\, dx_b\, f_{a/A}(x_a, Q^2)\, f_{b/B}(x_b, Q^2)$$
$$\times \quad \frac{1}{\pi z} \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(\hat{s}, \hat{t}, \hat{u}, x_a, x_b)\, D_{C/c}(z, Q^2)$$

$f_{a/A}(x_a, Q^2),\ f_{a/A}(x_a, Q^2)$
$D_{C/c}(z, Q^2)$

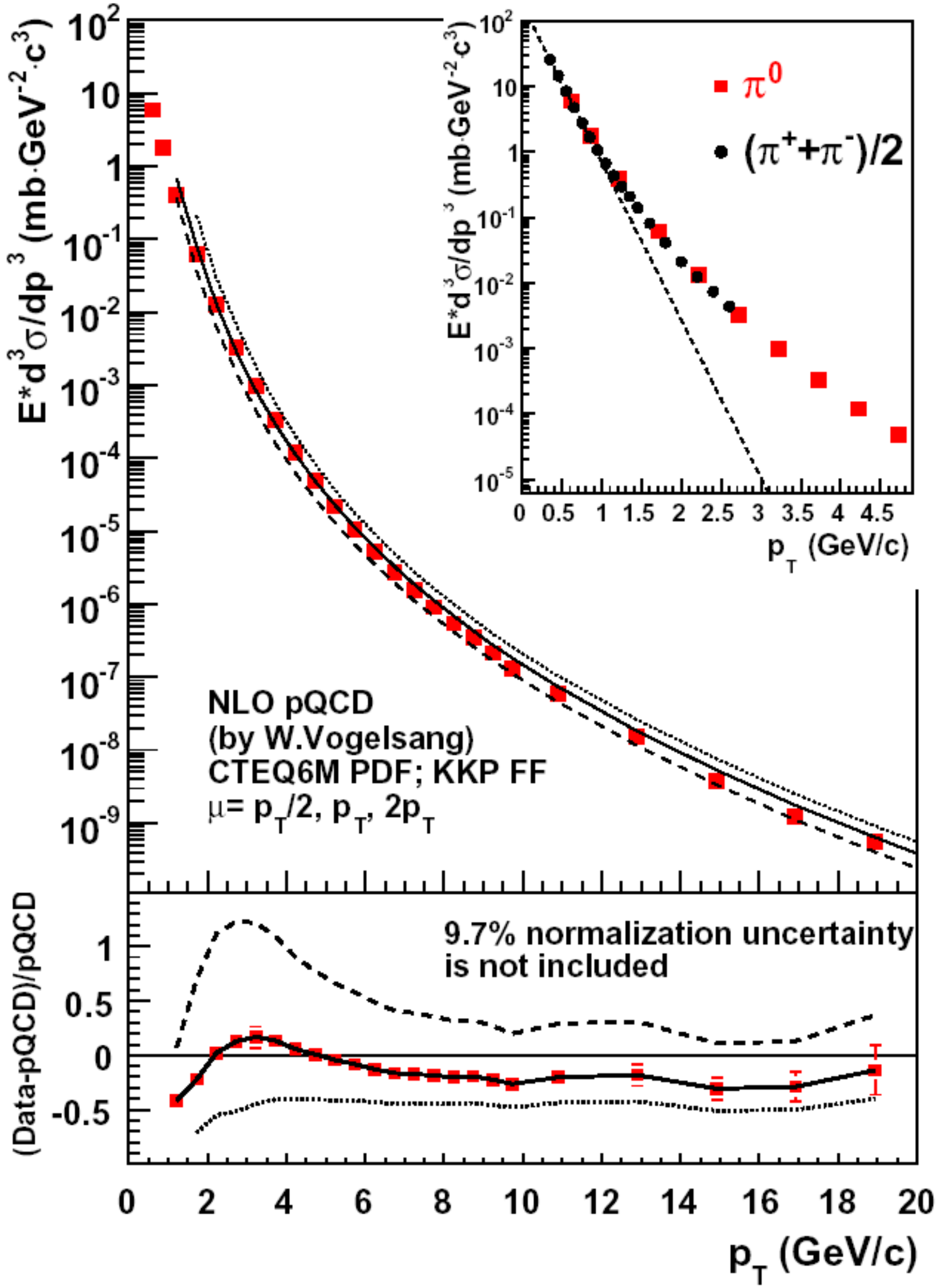
partonic distributions and fragmentation functions: from DIS, e+e-,... data, evolved at the Q^2 of interest, $Q^2 \approx p_T$

$d\hat{\sigma}^{ab\to cd}$

elementary partonic interactions, pQCD

$\hat{s},\ \hat{t},\ \hat{u}$

Mandelstam variables of elementary process



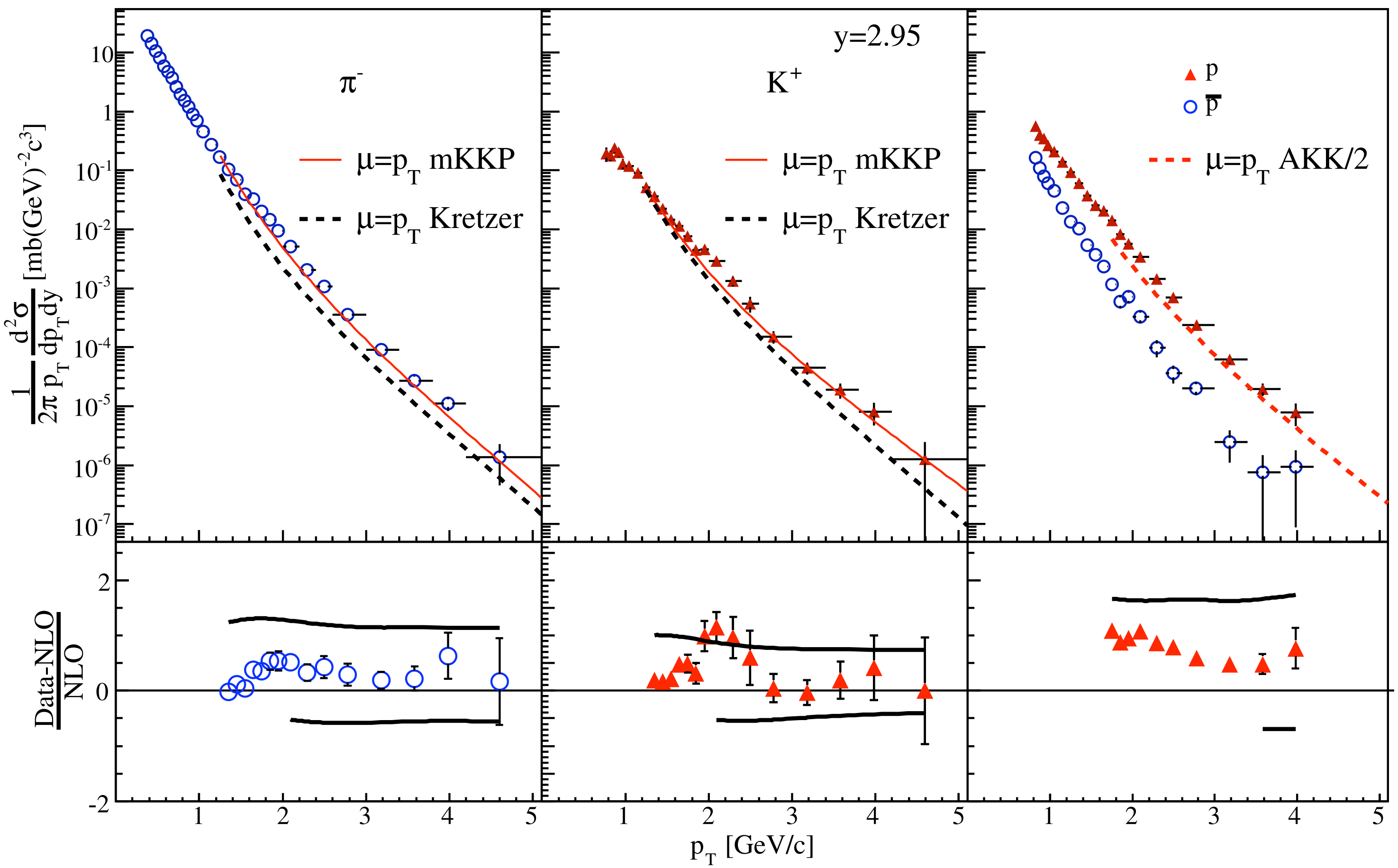
it works very well
at high energies!

RHIC, $p\,p \rightarrow \pi\, X$

$\sqrt{s} = 200\,\mathrm{GeV}$

PHENIX data on
unpolarized cross
section

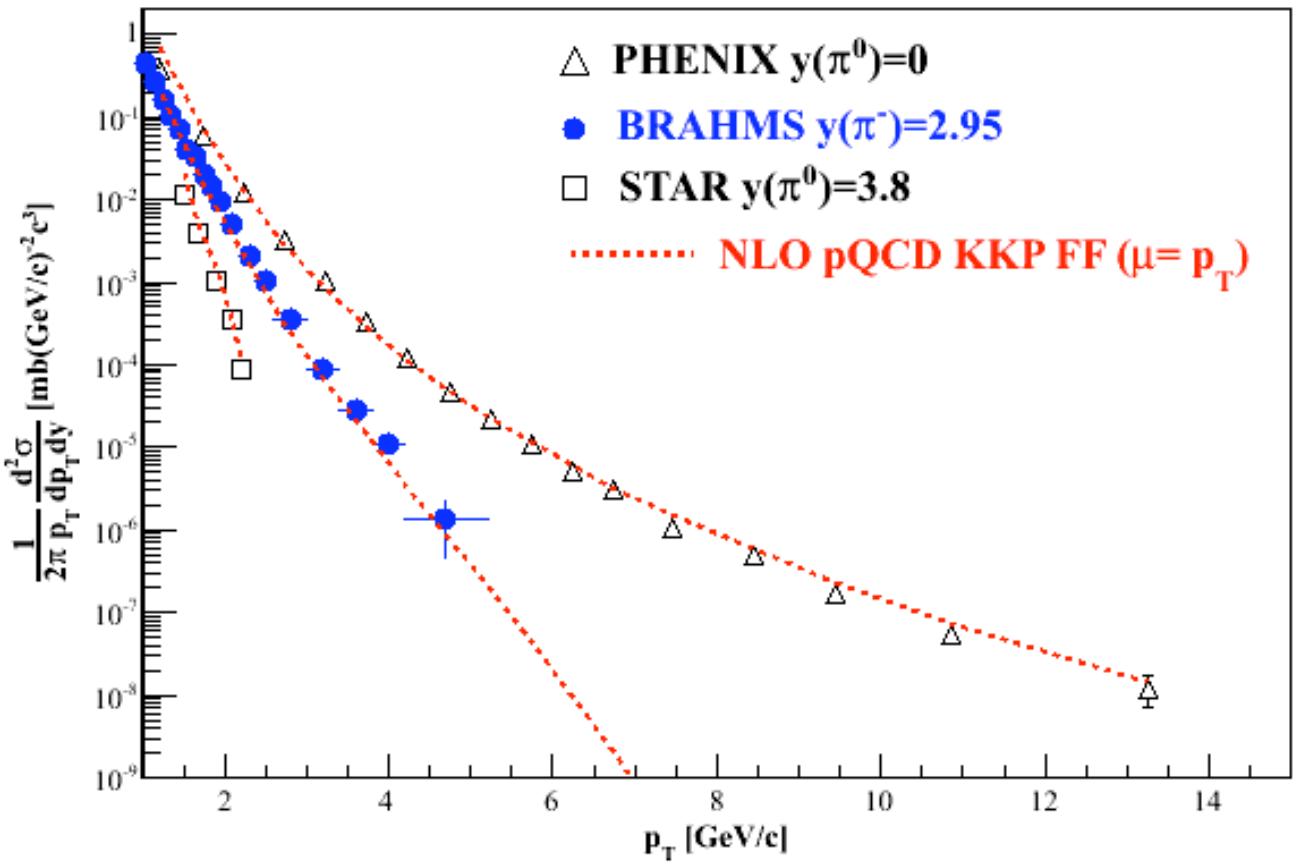
BRAHMS, proton-proton at 200 GeV



Phys. Rev. Lett. 98, 252001 (2007)

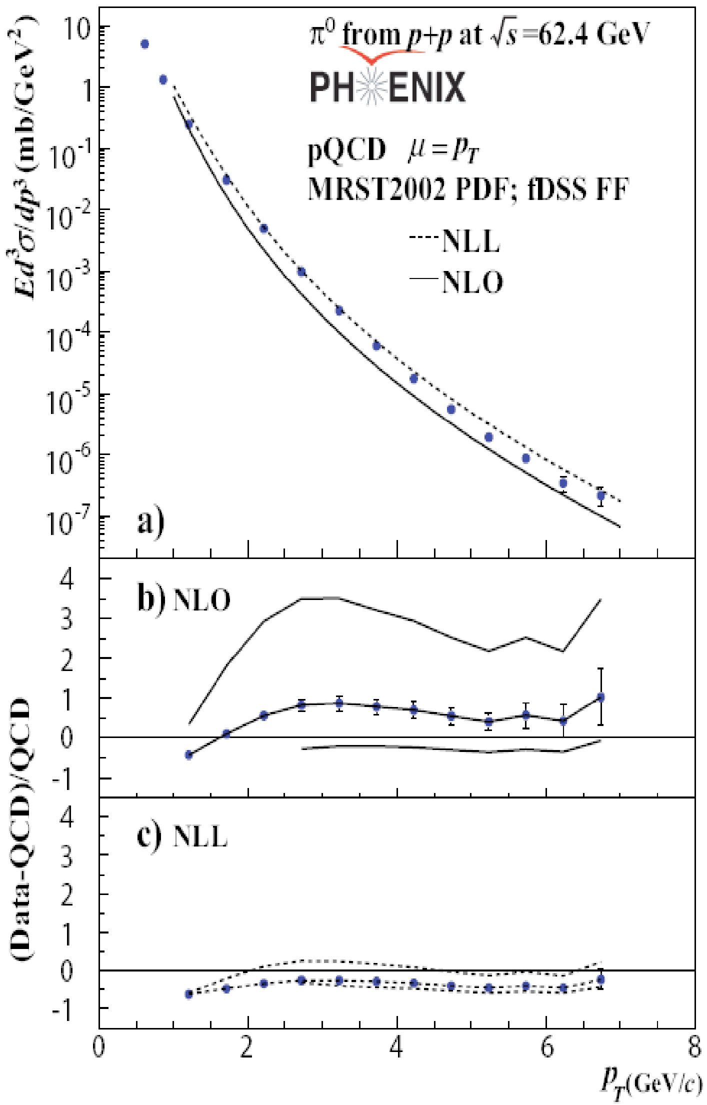
Polarization-averaged cross sections at $\sqrt{s}$=200 GeV

(talk of C. Aidala at Transversity 2008, May 2008, Ferrara)



good pQCD description of data at 200 GeV, at all rapidities, down to p_T of 1-2 GeV/c

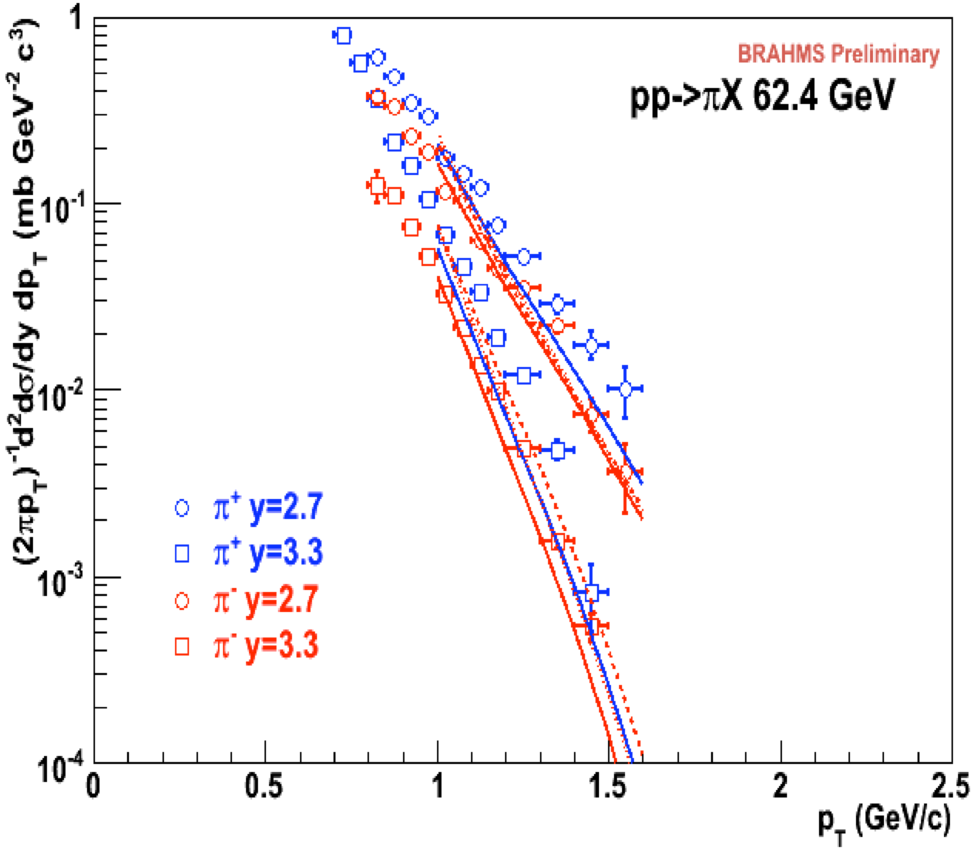
C. Aidala talk, data points from arXiv:0801.4555



$\sqrt{s}$=62.4 GeV
midrapidity pions

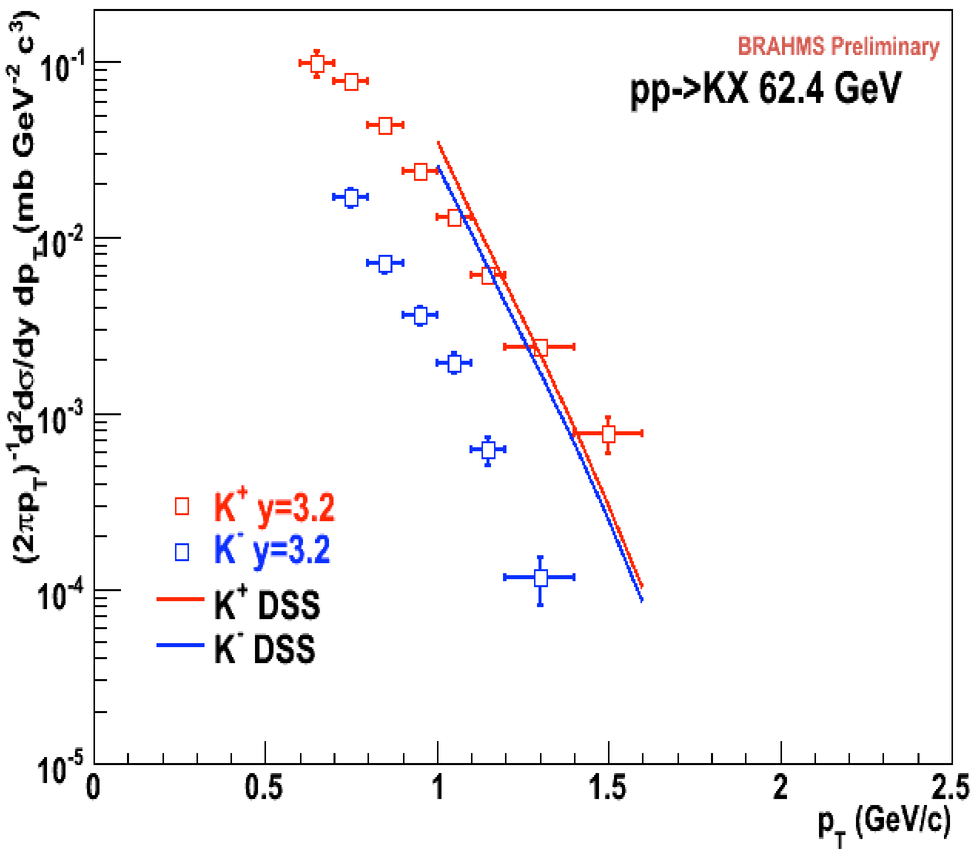
rather good agreement
with theory

$\sqrt{s}$=62.4 GeV
forward pions



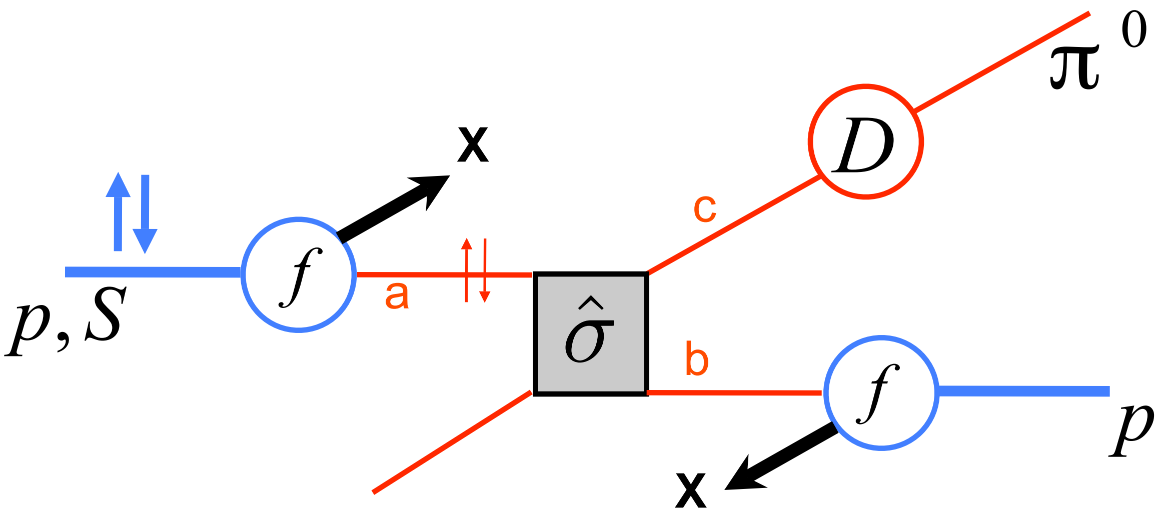
still good agreement with data, in disagreement with earlier analysis of ISR π^0 data at 53 GeV.

√s=62.4 GeV
forward kaons



K^+ fine, problems with K^-

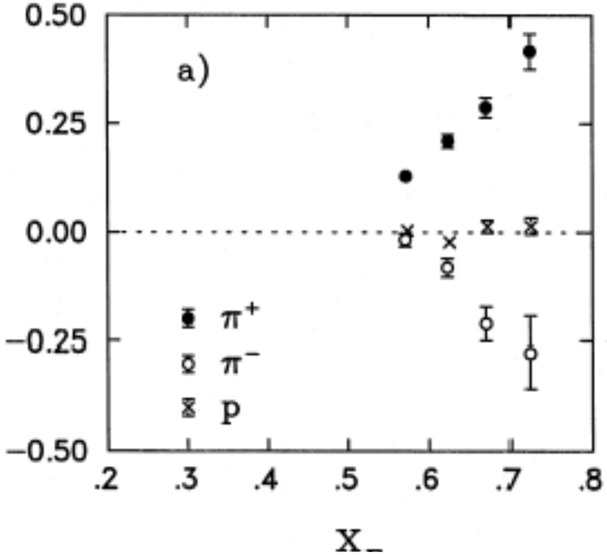
SSA?



$$d\sigma^{\uparrow} - d\sigma^{\downarrow} = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{\Delta_T f_a}_{\text{transversity}} \otimes f_b \otimes \underbrace{[d\hat{\sigma}^{\uparrow} - d\hat{\sigma}^{\downarrow}]}_{\text{pQCD elementary SSA}} \otimes \underbrace{D_{\pi/c}}_{\text{FF}}$$

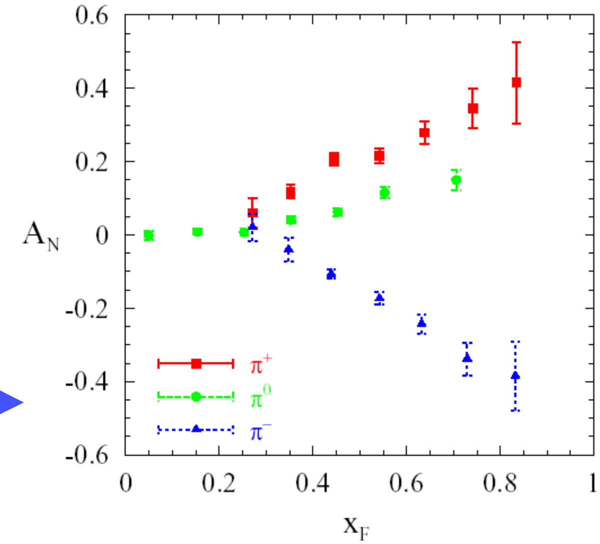
$$\Rightarrow \quad A_N \propto \hat{a}_N \propto \frac{m_q}{E_q} \alpha_s$$

was considered almost a theorem

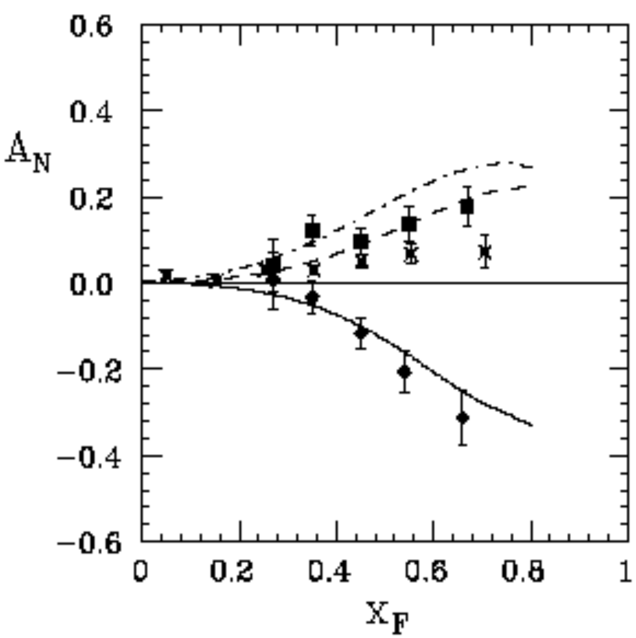


BNL-AGS $\sqrt{s}$ = 6.6 GeV
$0.6 < p_T < 1.2$

$$\boxed{p^\uparrow p \longrightarrow \pi\, X}$$



E704 $\sqrt{s}$ = 20 GeV
$0.7 < p_T < 2.0$



observed transverse Single Spin Asymmetries

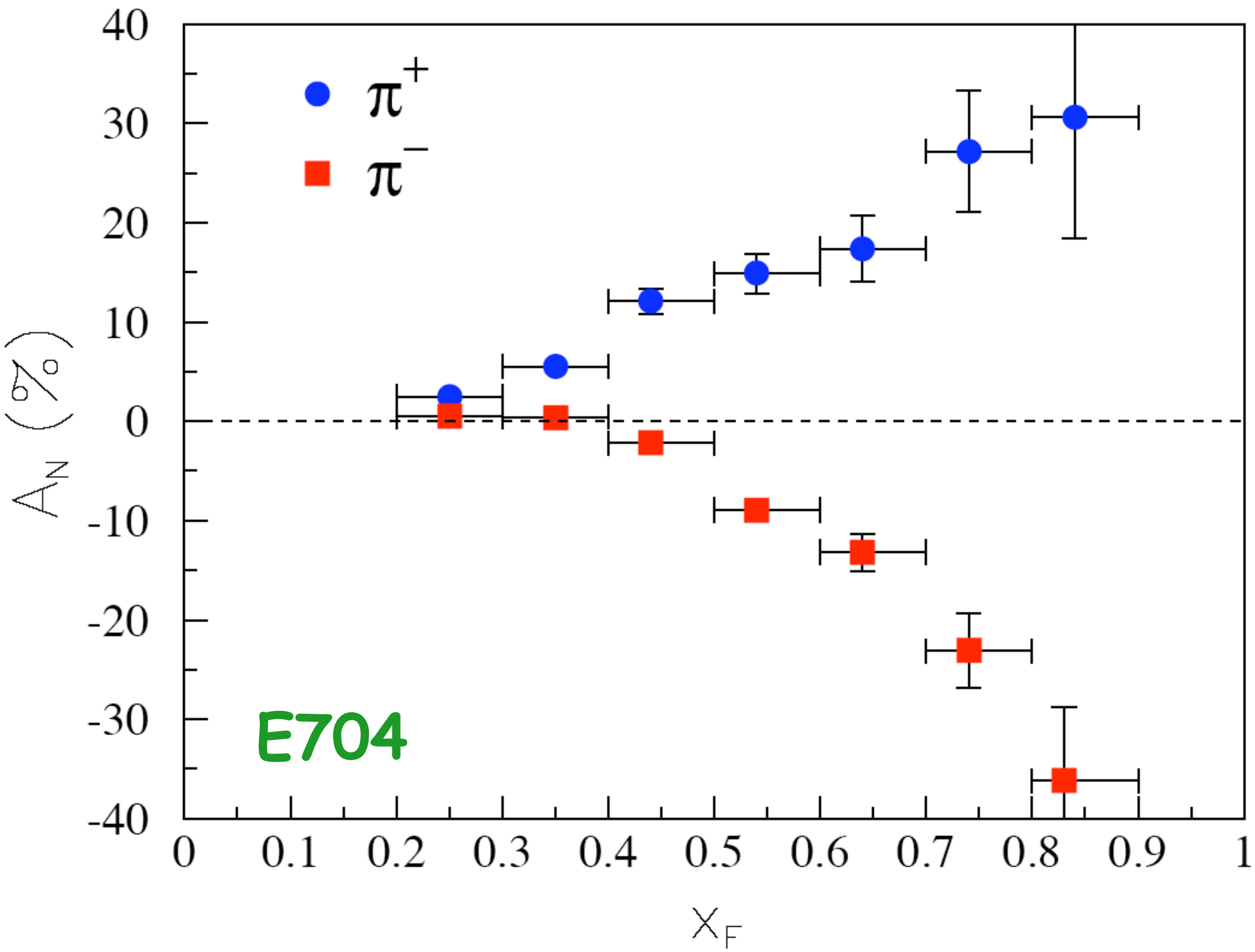
E704 $\sqrt{s}$ = 20 GeV
$0.7 < p_T < 2.0$

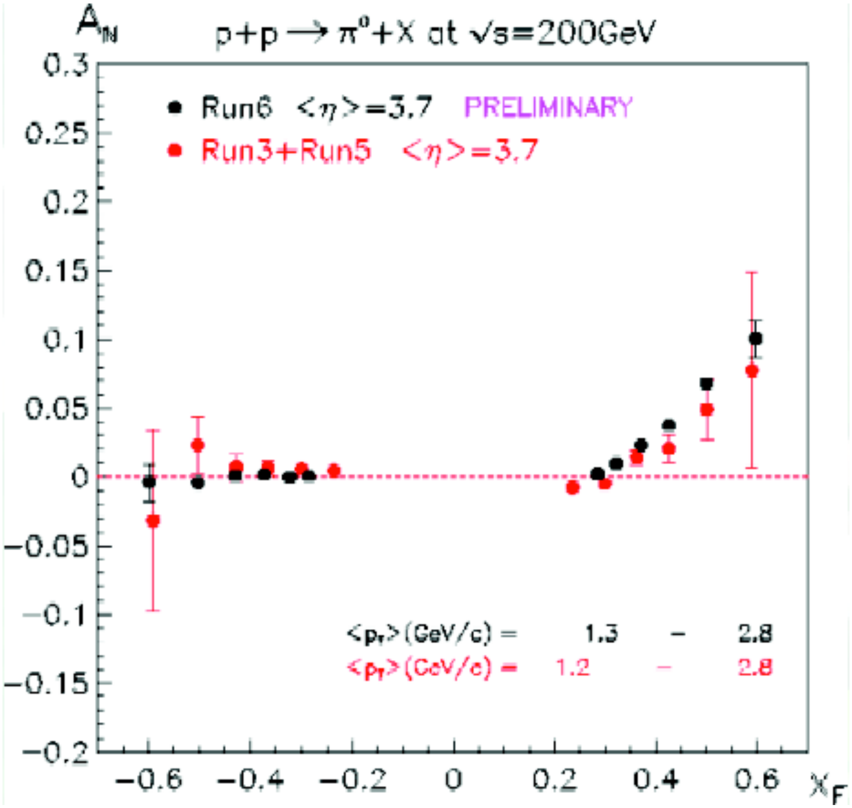
$$\boxed{\bar{p}^\uparrow p \longrightarrow \pi\, X}$$

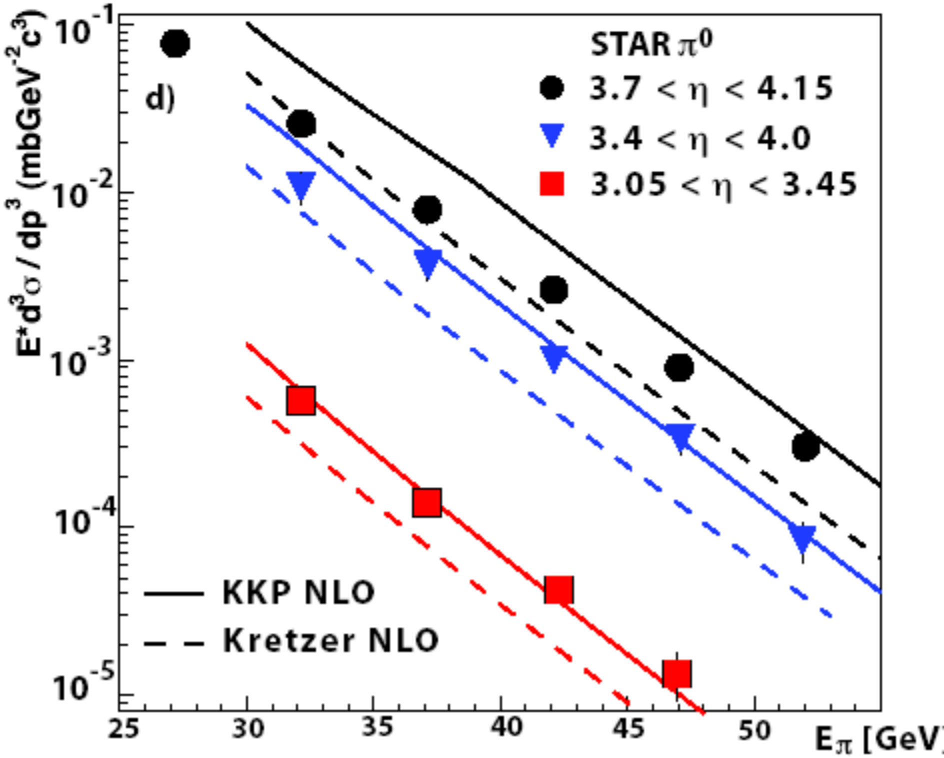
$$A_N \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

experimental data on SSA

E704 $\sqrt{s}$ = 20 GeV $0.7 < p_T < 2.0$

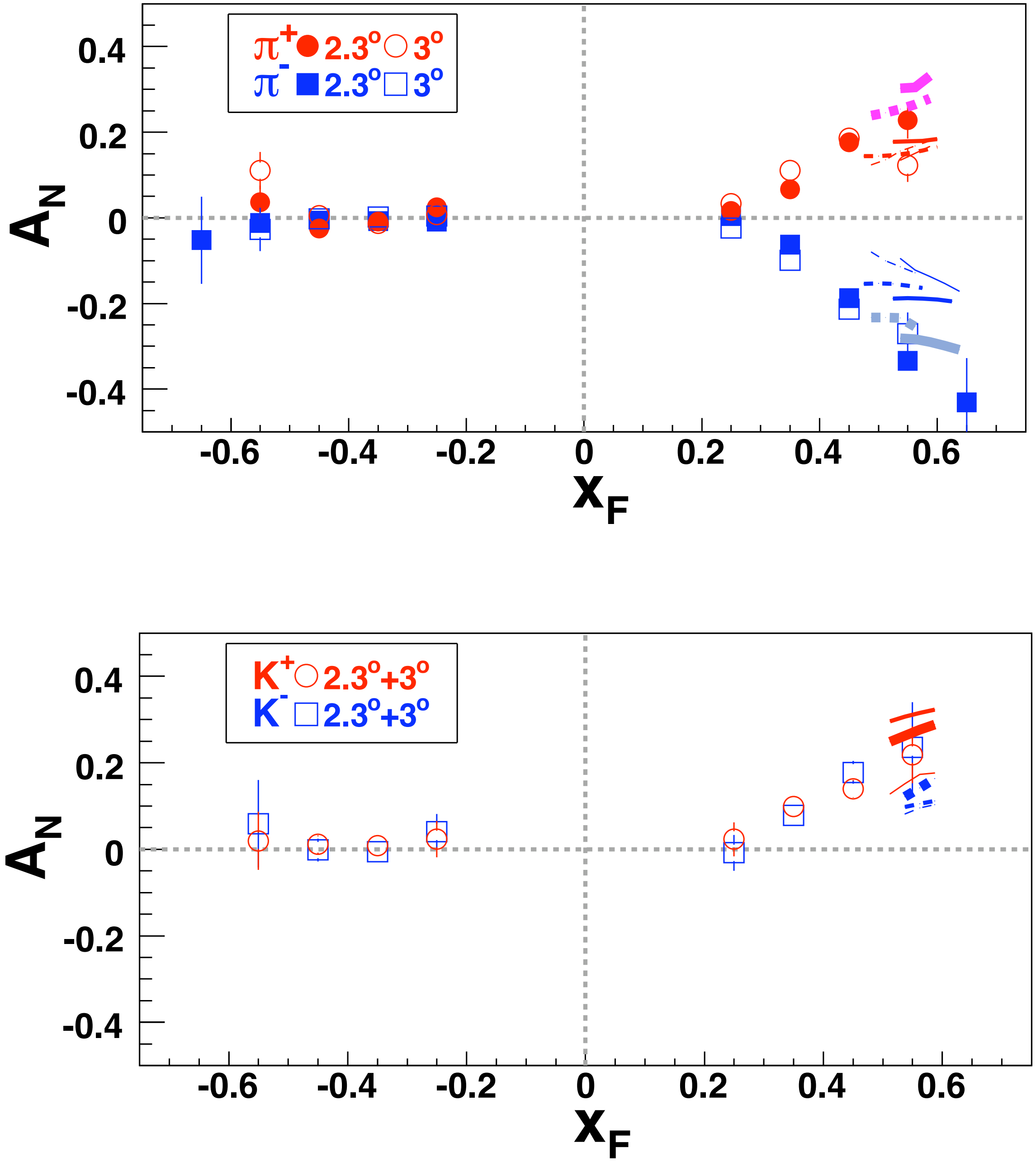






STAR-RHIC $\sqrt{s}$ = 200 GeV $1.2 < p_T < 2.8$

and A_N stays at high energies ….

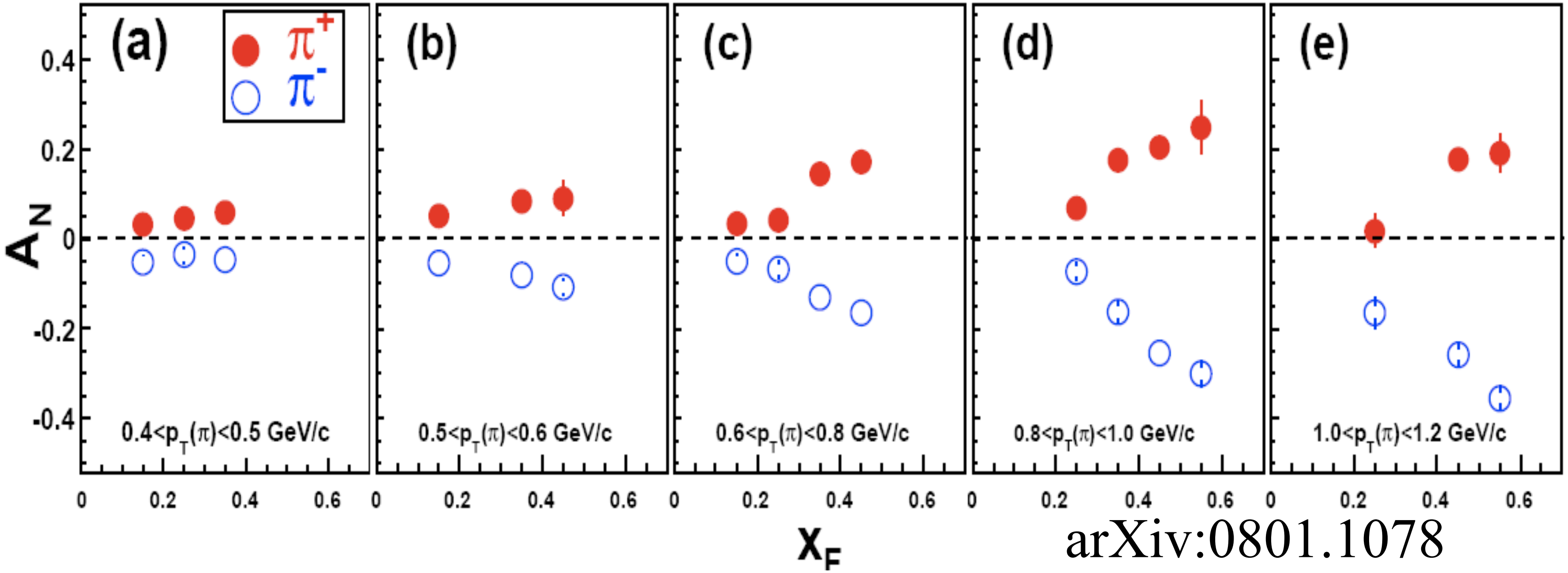


and data keep coming ...

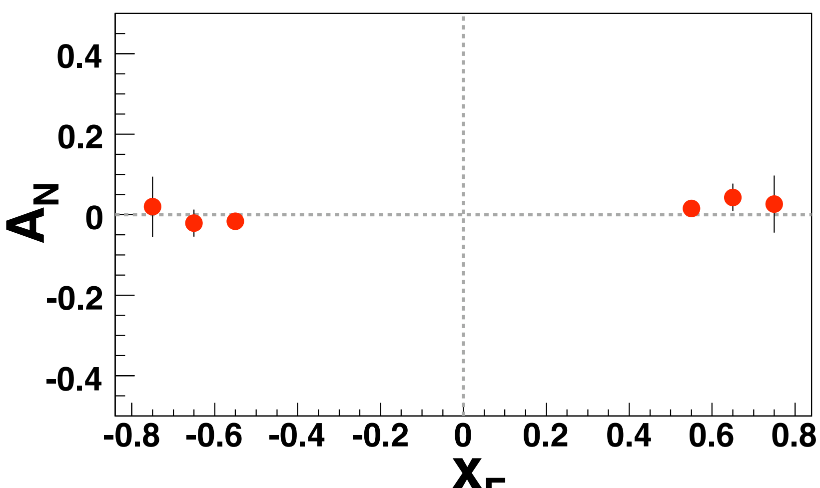
PRL 101, 042001 (2008)

pion and Kaon SSA, measured by BRAHMS at $\sqrt{s}$ = 62.4 GeV

A_N x_F-p_T dependence at $\sqrt{s}$ = 62.4 GeV



arXiv:0801.1078

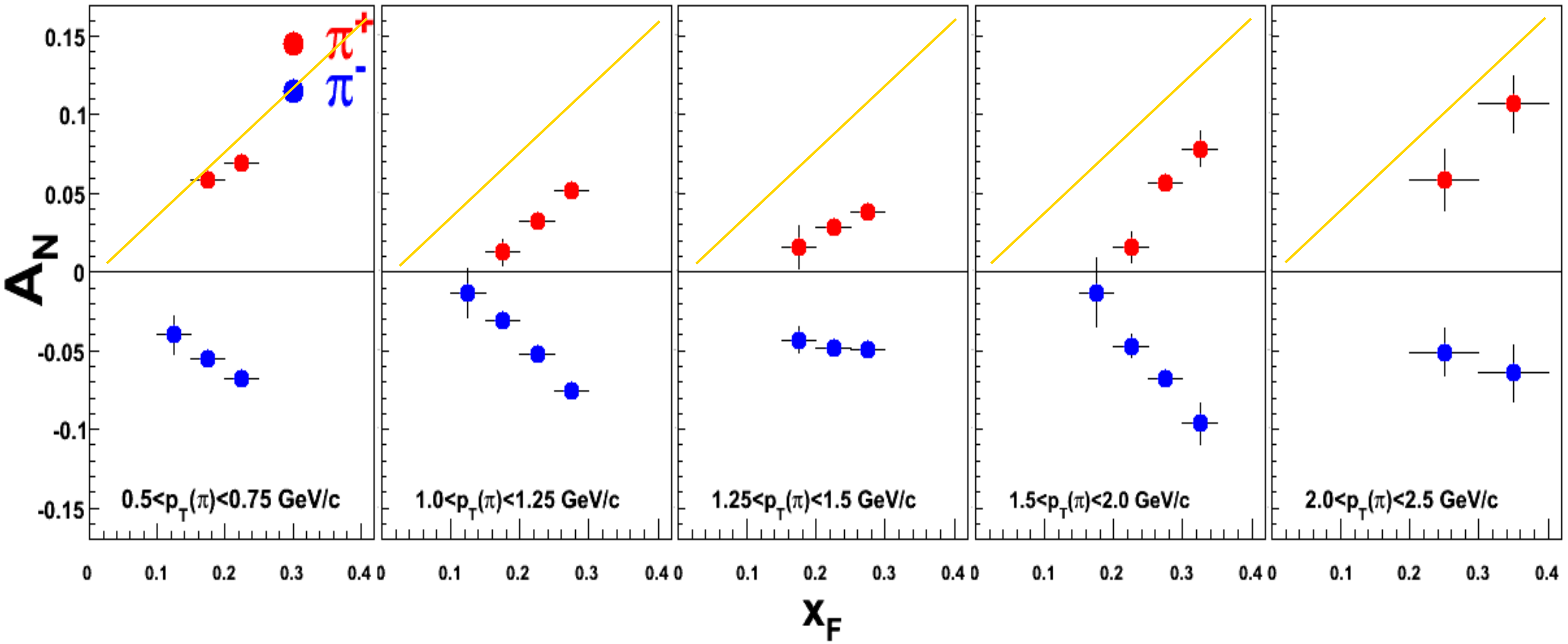


$A_N \approx 0$ for proton

BRAHMS

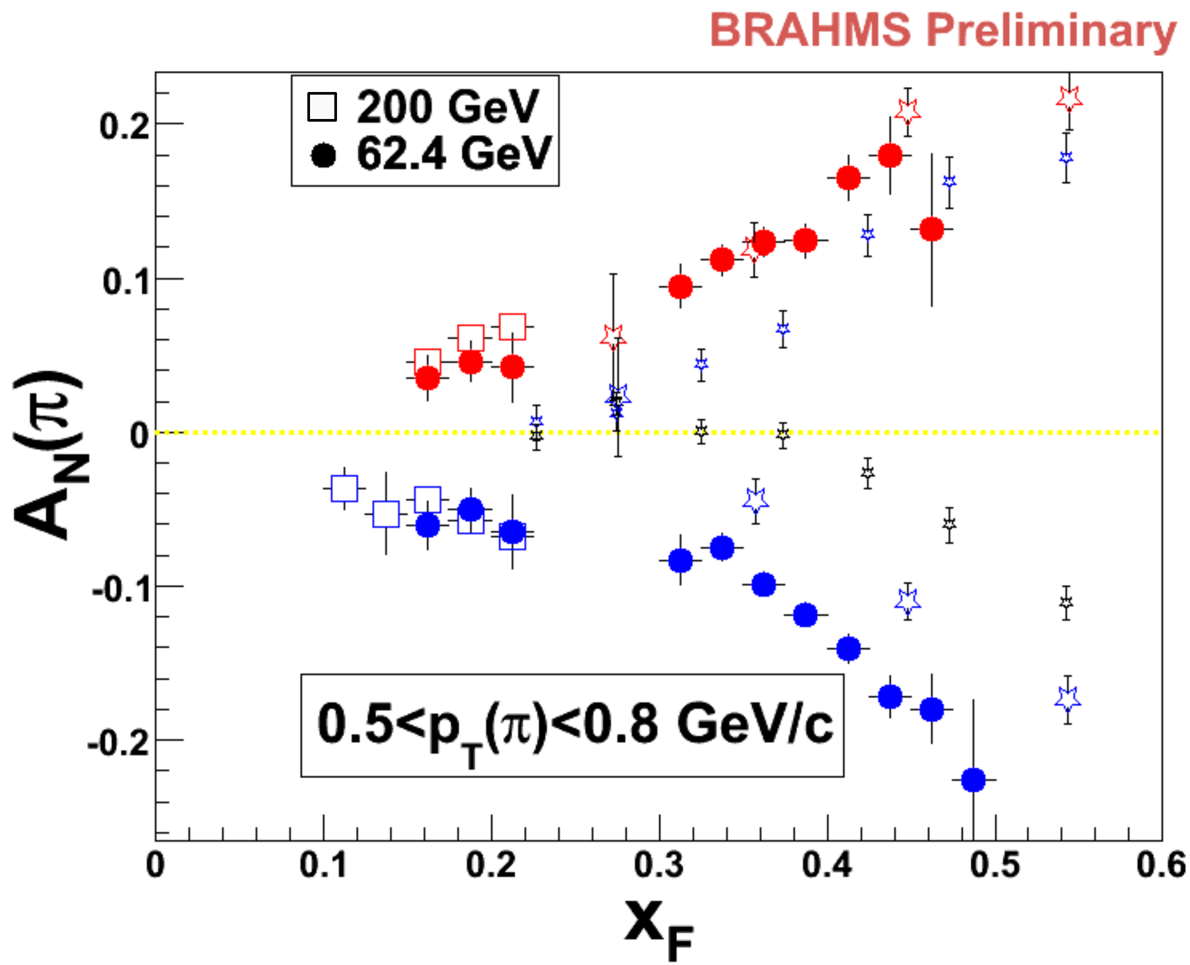
A_N x_F-dependence in p_T slices, $\sqrt{s}$ = 200 GeV

(C. Aidala talk at Transversity 2008)



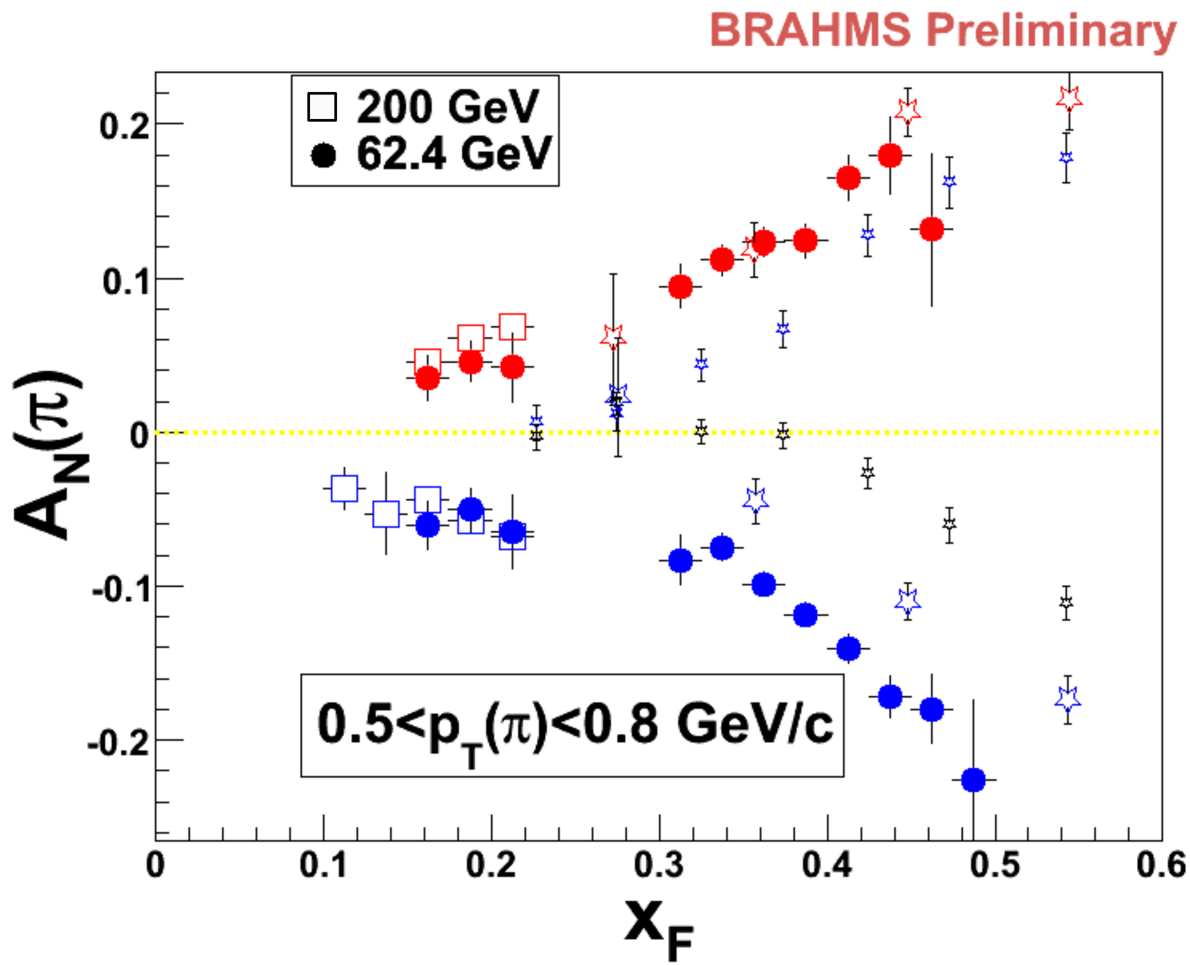
Unifying 62.4 and 200 GeV, BRAHMS + E704

(C. Aidala talk at transversity 2008, Ferrara)



Unifying 62.4 and 200 GeV, BRAHMS + E704

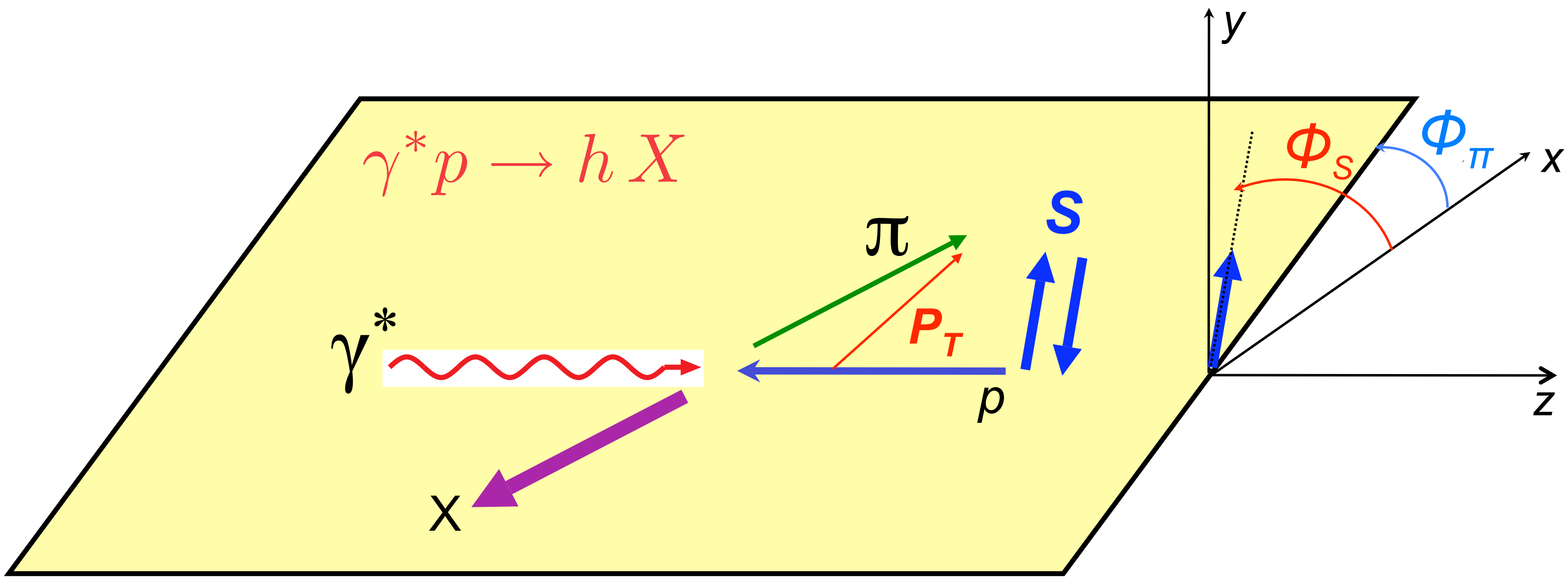
(C. Aidala talk at transversity 2008, Ferrara)



E704 data – all p_T (small stars); p_T>0.7 GeV/c (large stars)

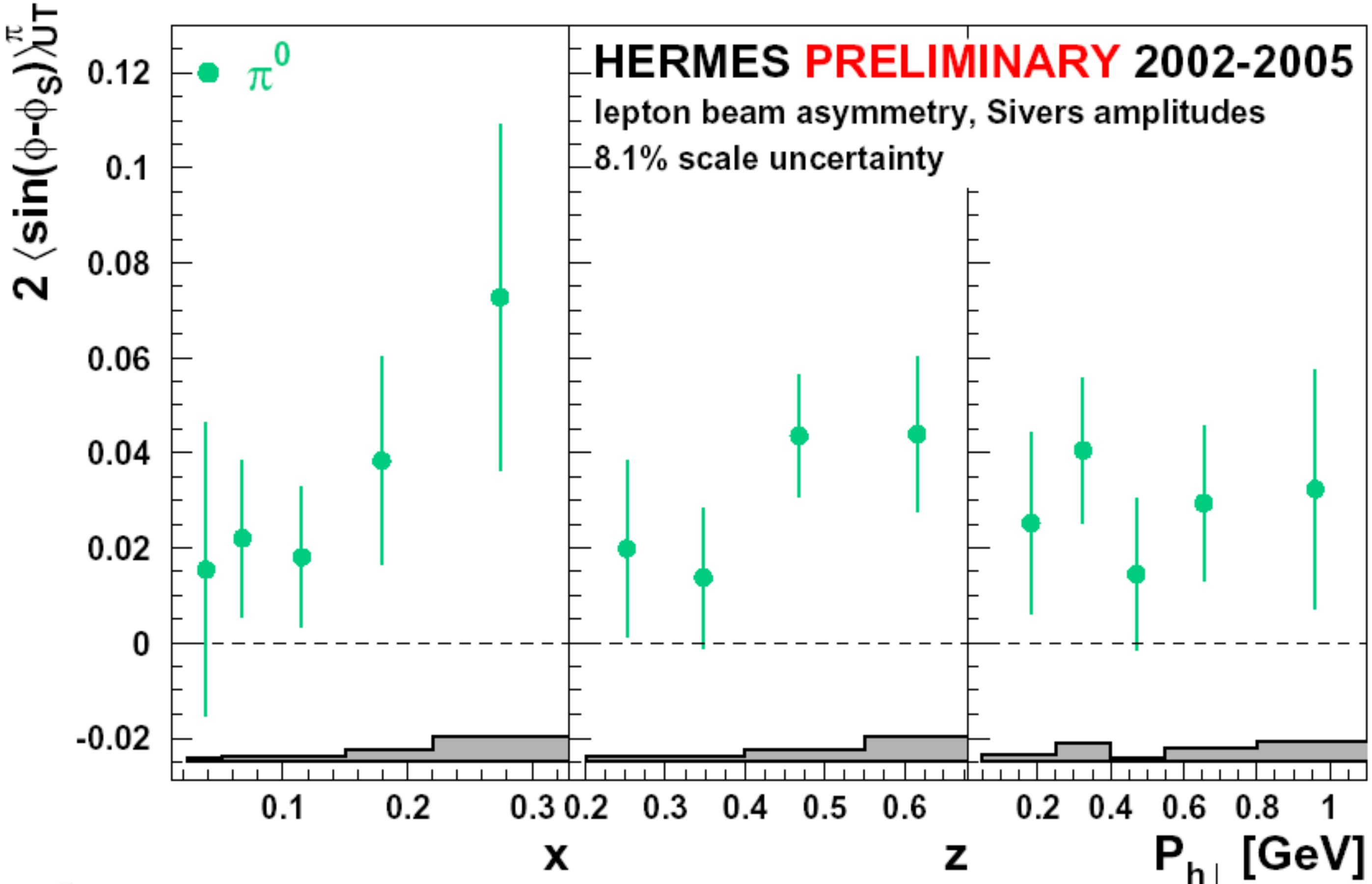
Transverse single spin asymmetries in SIDIS, experimentally observed

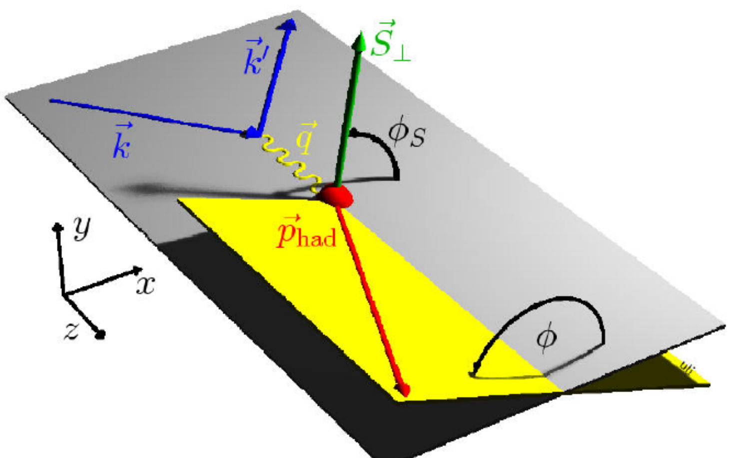
$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$



$$A_N \propto \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{P}_T) \propto P_T \sin(\Phi_\pi - \Phi_S) \qquad \gamma^* - p \ \text{c.m. frame}$$

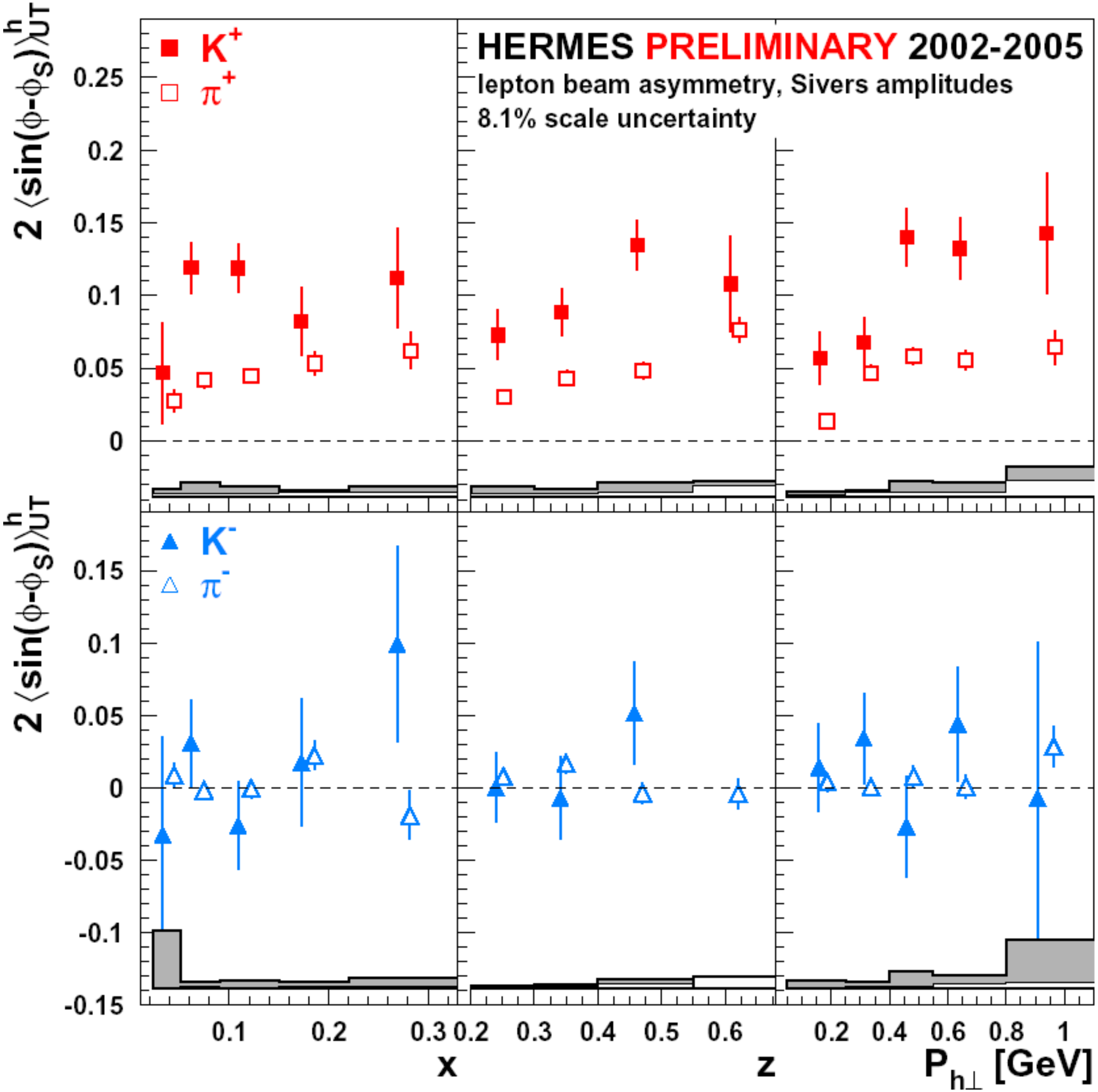
in collinear configurations there cannot be (at LO) any P_T



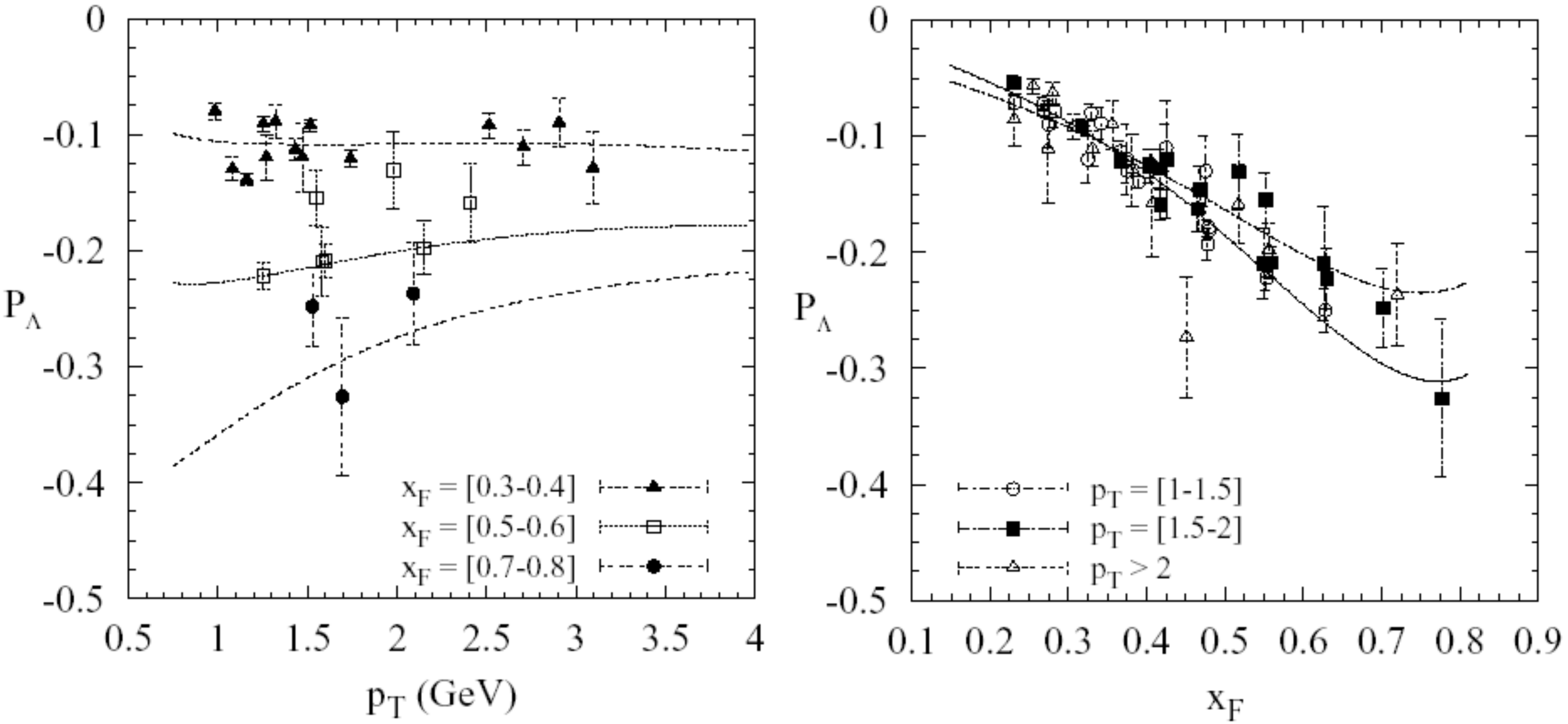


$$2\langle\sin(\Phi-\Phi_S)\rangle = A_{UT}^{\sin(\Phi-\Phi_S)}$$

$$\equiv \frac{\int \mathrm{d}\Phi\,\mathrm{d}\Phi_S\,(\mathrm{d}\sigma^{\uparrow}-\mathrm{d}\sigma^{\downarrow})\,\sin(\Phi-\Phi_S)}{\int \mathrm{d}\Phi\,\mathrm{d}\Phi_S\,(\mathrm{d}\sigma^{\uparrow}+\mathrm{d}\sigma^{\downarrow})}$$



New kaon data, large K^+ asymmetry!

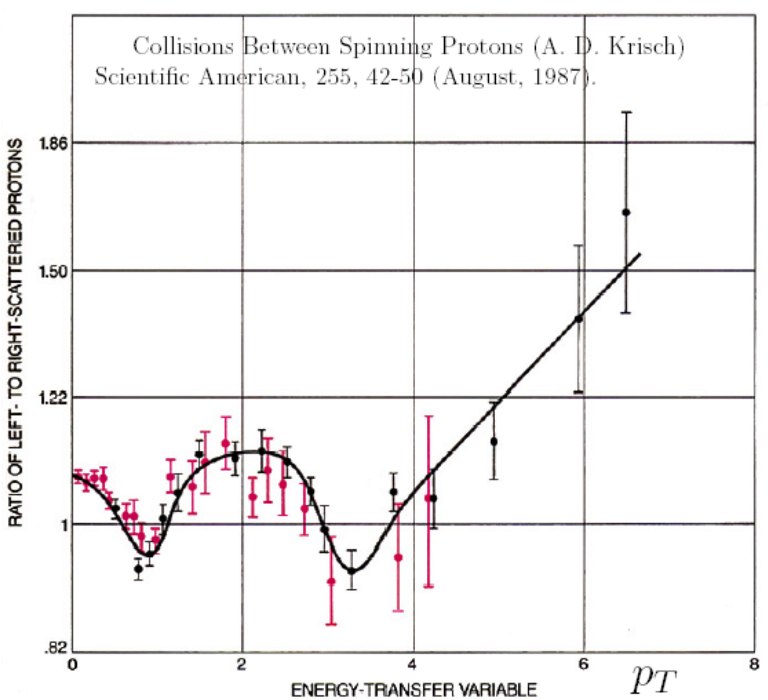


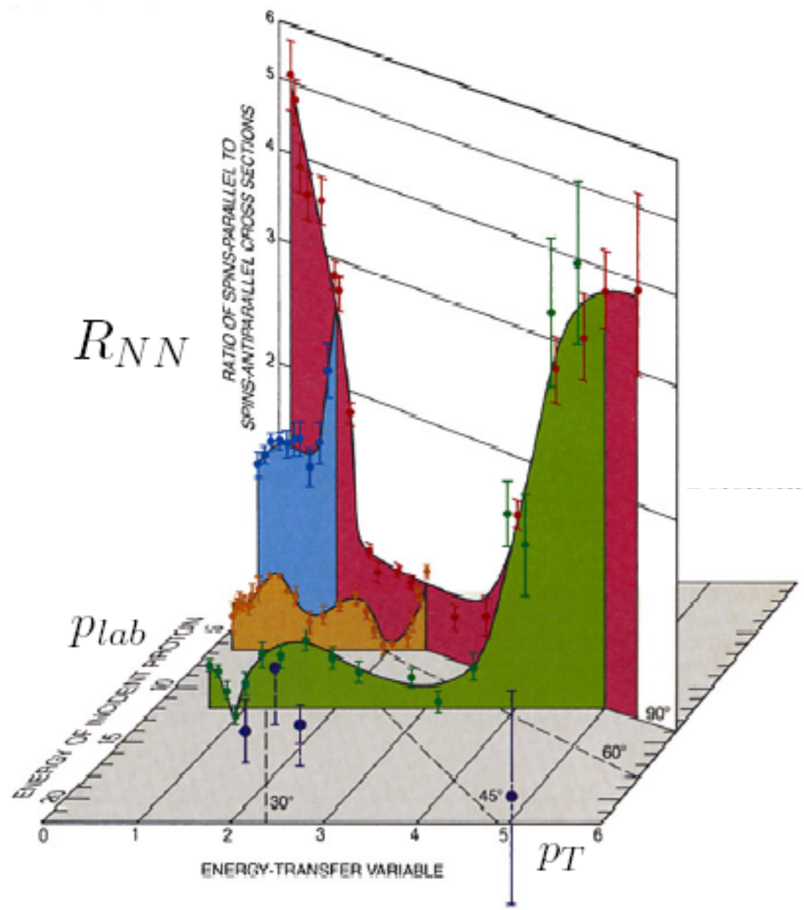
Transverse Λ polarization in unpolarized p-Be scattering at Fermilab

$$p\,N \to \Lambda^{\uparrow}\,X$$

$$p^{\uparrow} p \to p\, p$$

$$p^{\uparrow} p^{\uparrow} \to p\, p$$





And now .... ?

Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might just ban such measurements altogether out of self-protection.

J.D. Bjorken
St. Croix, 1987